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Overview of the Lunar In Situ Resource Utilization Techniques for Future Lunar Missions

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Along with the rapid development of space technology, extraterrestrial exploration has gradually tended to further-distanced and longer-termed planet exploration. As the first step of an attempt for humans to build a perpetual planet base, building a lunar base by in situ resource utilization (ISRU) will drastically reduce the reliance of supplies from Earth. Lunar resources including mineral resources, water/ice resources, volatiles, and solar energy will contribute to the establishment of a lunar base for long-term life support and scientific exploration missions, although we must consider the challenges from high vacuum, low gravity, extreme temperature conditions, etc. This article provides a comprehensive review of the past developing processes of ISRU and the latest progress of several ISRU technologies, including in situ water access, in situ oxygen production, in situ construction and manufacture, in situ energy utilization, and in situ life support and plant cultivation on the Moon. Despite being able to provide some material and energy supplies for lunar base construction and scientific exploration, the ISRU technologies need continuous validation and upgrade to satisfy the higher requirements from further lunar exploration missions. Ultimately, a 3-step development plan for lunar ISRU technologies in the next decade is proposed, which consists of providing technological solutions, conducting technical verification on payloads, and carrying out in situ experiments, with the ultimate aim of establishing a permanent lunar station and carrying out long-term lunar surface scientific activities. The overview of ISRU techniques and our suggestions will provide potential guidance for China's future lunar exploration missions.

Introduction

As the only natural satellite of Earth, the Moon owns a special space environment, unique space position, and abundant natural resources, which are very crucial for mankind's moves toward deep space. Thus, it is the first target for human deep-space exploration and the ideal destination for building a permanent scientific station. In specific, the lunar surface has a special environment of high vacuum, low gravity, extreme temperature conditions, etc. These unique environmental conditions offer favorable factors for the establishment of astronomical observation stations, scientific experiment bases, biological products and new material research laboratories, Earth observation sites, and deep-space exploration outposts, which are of great significance for progress in lunar science research, lunar-based science research, and deep-space exploration technologies. In addition, the rich mineral resources, water/ice resources, energy resources, and special space conditions of the Moon have shown wide prospects of development and utilization, which will provide basic survival matters and security facilities for the long-term activities of human beings on the lunar surface, thus expand the frontiers of human beings, and serve the sustainable development of human society.

Past lunar exploration missions have greatly promoted human understanding of the Moon, Earth–Moon, and Solar Systems. So far, mankind has sent more than 100 lunar exploration spacecrafts, obtained extremely rich exploration data, and collected about 384 kg of lunar samples. The Apollo program is the only successful manned lunar exploration program so far. It carried out 6 missions and sent 12 people to the Moon. At the same time, nearly 30 scientific explorations and experiments on the lunar surface, including lunar geological investigation, lunar interior structure detection, lunar environment exploration, and lunar sample collection, were completed during these missions. The scientific achievements of the Apollo program are the foundation of primary scientific understanding of the Moon up to now [1]. In the aspect of unmanned lunar exploration, the Soviet Union carried out full-Moon mapping and historical exploration of topography, geological structure, lunar soil characteristics, and space environment by the "Luna" and "Zond" series Lunar probes. The United States, Europe, Japan, and India have launched the Clementine and Lunar Prospectors, Lunar Atmosphere and Dust Environment Explorer, Lunar Gravity Recovery and Interior Laboratory, Lunar Reconnaissance Orbiter, Smart-1, SELENE Moon Goddess, Chandrayaan-1, and other spacecrafts, which have carried out a comprehensive survey of global lunar topography, lunar space environment, and lunar resources. Through the above exploration activities, a series of breakthroughs have been made in the study of the Moon, and a large number of new understandings have been gained on the origin of the Moon, Earth–Moon system, and the Solar System. Lunar exploration in the future shows the following trends:

1. The focus of future lunar exploration will gradually shift from understanding the Moon to making use of the Moon.
2. The future lunar exploration mode will change from short-term exploration to long-term residence and will gradually focus on resource-rich areas such as the lunar South Pole.
3. Because of the difficulty, high risk, and high cost of lunar exploration technology, international cooperation can share the costs and risks and share the achievements and developments; thus, it is the general trend of future lunar exploration missions.

Up to now, lunar exploration missions must bring all the supplies from Earth. The cost, technical difficulty, and launching window limitations of carrying supplies from Earth will create significant obstacles to future lunar exploration and other deep-space exploration missions. In situ resource utilization (ISRU) is the mining, treatment, and utilization of natural resources, including lunar minerals, water/ice resources, volatiles, and solar energy from the Moon [2,3]. The ISRU program has been listed as the main goal of the incoming Lunar exploration missions, such as the National Aeronautics and Space Administration's (NASA's) Artemis program [4–6], China's International Lunar Research Station Program (ILRS) [7,8], and European Space Agency's (ESA's) Lunar Exploration missions [9,10]. The technology processes of ISRU on the Moon mainly include excavation, beneficiation, transformation, extraction, storage, conversion, and utilization of lunar natural resources [11,12]. The ISRU on the Moon is considered to be the most promising method to enable sustainable deep-space exploration by providing some of the vital products and consumables without supplies from Earth [13]. Major purposes of lunar ISRU development for future robotic and manned exploration missions include the following:

1. In situ supply of life-supporting matters, including water, oxygen, food, solar/electric energy, etc.
2. Construction and manufacturing of key facilities, including manned habitat, landing pads, scientific facilities, transport tools, and maintenance tools.
3. In situ supply of lunar-based rocket propellant, including hydrogen, oxygen, methane (CH_4), etc.
4. Matter and facility supporting for lunar-based scientific research.
5. Transit and supply stations in cislunar space for Mars and other deep-space missions.

Thus, the lunar ISRU technology would make the lunar missions and other deep-space exploration missions sustainable in the long term by reducing the mass and cost of deep-space missions, getting rid of launch window limitations, extending the survival frontiers of mankind, and mitigating the risk of humans going to and returning from the extraterrestrial bodies. During the past 50 years, a lot of research work had been done on several aspects of ISRU techniques for proof-of-concept demonstrations under laboratory conditions. These works will provide a foundation for the development of ISRU techniques in future lunar exploration missions. The present article gives a comprehensive review of the past developing processes of lunar ISRU and the latest progress of several technologies, including in situ water access, oxygen production, in situ construction and manufacture, energy utilization, and in situ life support and plant cultivation on the Moon surface. The basic principles, technique schemes, proof-of-principle experiments, and results of these technologies are introduced in detail. Furthermore, according to development roadmaps of future lunar exploration missions, we also propose recommendations of priorities for ISRU technologies and roadmaps of future development. This review article will provide potential guidance for China's future lunar exploration missions.

The ISRU Techniques on the Moon

Natural resources on the Moon

With the development of lunar exploration projects in various countries, many remote-sensing missions have been carried out over the past 20 years [14]. At the same time, the analysis of samples during the Apollo missions was continued conducted over the past 50 years [3,14]. According to the data obtained by the Apollo project, a comprehensive assessment of lunar natural resources has been given on the basis of the knowledge of the early 1990s, and it was updated by Duke et al. [15], Schrunk et al. [16], Anand et al. [17], and Crawford [18]. The main natural resources of the Moon include mineral resources, water/ice resources, volatiles, and solar energy.

Mineral resources

As represented in currently collected samples from Apollo and Chang'E missions, minerals of the lunar crust can be categorized as silicate minerals, oxide minerals, native metals, sulfide minerals, and phosphate minerals [19]. As shown in Table 1, silicate minerals are the most abundant components, making up more than 90% of the volume of most lunar rocks. Among the silicate minerals, pyroxene, plagioclase feldspar, and olivine are the most abundant minerals in lunar crust [3]. Other minerals such as zircon and potassium feldspar (K feldspar) are rare on the Moon but common on Earth [20,21]. Direct global measurements of the lunar surface were obtained by Greenhagen et al. [22] using multispectral thermal emission mapping. These data reveal the presence of a highly evolved, silica-rich lunar crust at the micrometer scale.

Following silicate minerals in abundance are oxide minerals, which consist mainly of metals and oxygen. They are particularly concentrated in mare basalts, which may account for up to 20% of the volume of these rocks. Oxygen usually exists in the form of iron oxide in iron-rich lunar minerals and glass [16,23]. Oxygen in oxide minerals binds weakly to that in silicate minerals; they are of great significance in the utilization of lunar oxygen and metals production. Several important oxide minerals are listed as follows: The most abundant oxide mineral include ilmenite, spinels, and armalcolite. The less abundant lunar oxide minerals include rutile, baddeleyite, and zirconolite. One of the most surprising findings from the returned lunar samples was the presence of native iron metal grains in each sample [24]. Up to now, several native metal

Table 1. Significant lunar mineral modal proportions (volume %) of minerals and glasses in soils from the Apollo (A) and Luna (L) sampling sites (90- to 20-μm fraction, not including fused-soil and rock fragments) [3].

	A	A	A-14	A-H	A-M	A-16	A-H	A-M	L-16	L-20	L-24
Plagioclase	21.4	23.2	31.8	34.1	12.9	69.1	39.3	34.1	14.2	52.1	20.9
Pyroxene	44.9	38.2	31.9	38.0	61.1	8.5	27.7	30.1	57.3	27.0	51.6
Olivine	2.1	5.4	6.7	5.9	5.3	3.9	11.6	0.2	10.0	6.6	17.5
Silica	0.7	1.1	0.7	0.9	–	0.0	0.1	–	0.0	0.5	1.7
Ilmenite	6.5	2.7	1.3	0.4	0.8	0.4	3.7	12.8	1.8	0.0	1.0
Mare glass	16.0	15.1	2.6	15.9	6.7	0.9	9.0	17.2	5.5	0.9	3.4
Highland glass	8.3	14.2	25.0	4.8	10.9	17.1	8.5	4.7	11.2	12.8	3.8
Others					2.3	–	–	0.7	–	–	
Total	99.9	99.9			100.0	99.9	99.9	99.8	100.0	99.9	99.9

H, highland; M, mare.

minerals have been identified including nickel, copper, kamacite (a-FeNi), molybdenum, Cr, cerium, rhenium, and zinc [25].

Water/ice resources

As we have learned from Moon samples and remote-sensing data analysis, the water on the Moon is highly depleted compared to that on Earth. However, in recent years, lunar exploration has shown that the Moon's surface environment may contain potentially water reservoirs [26]. Most of the water resources are in the form of mixed water ice in the polar lunar soils, except for the very few volatile (OH/H_2O) resources that have been found. Neutron spectrometers on the Lunar Prospector provided indirect evidence of ice in polar craters. Hayne et al. [27,28] described the spatial heterogeneous distribution of water frost (Fig. 1). Thus, the total mass of water contained within the uppermost meter of permanently shadowed regions (PSRs) was approximately about 2.9×10^{12} kg [18]. In addition to the water resources in polar craters, laboratory measurements of water contents of the Apollo 15 and 17 samples were mostly in the 5 to 30 parts per million (ppm) range [29]. Moreover, data analysis of infrared remote sensing observations indicates that some pyroclastic deposits may contain as much as 1,500 ppm of water [30]. The results of the latest study from Chang'E-5 samples estimated that the water content in lunar soils was at least 170 ppm. The results provide a reference for the distribution of surface water in the middle latitude of the Moon [31].

Volatiles resources

The review of concentrations of volatiles implanted by solar wind in the lunar regolith has been conducted [32,33]. Learned from the Apollo and Luna samples, the average concentrations are shown in Table 2.

In addition to the above volatiles, lunar soils contain small quantities of Ne and Ar. However, most interest has focused on the ^{3}He because it can be used for nuclear fusion reactors to produce electrical power. Despite some opinions that ^{3}He is abundant on the Moon [34], the highest measured concentrations of ^{3}He in lunar samples is about 10 parts per billion. So we must face up to the fact that the ^{3}He isotope is very rare in lunar soils.

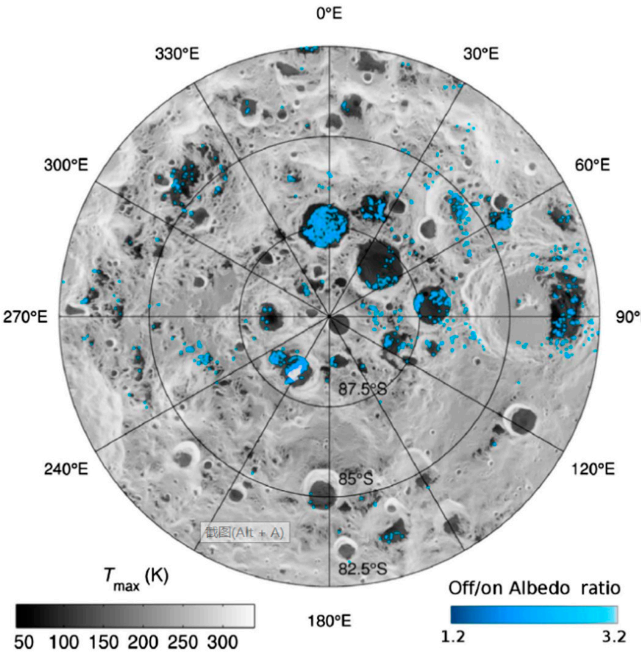

Fig. 1. Locations of anomalous ultraviolet albedo consistent with water ice [28].

Solar energy

The lunar environment is very different from Earth, the surface of the Moon has no atmosphere, solar radiation can be driven straight in, and the radiant energy flux contributes an average of about 1.1×10^{13} ergs/cm^2 per year to the lunar surface. Furthermore, in some polar regions, nonpermanently shaded areas can provide an unlimited supply of solar energy [35]. As we expected, solar energy has the potential to be an imported lunar export, as it can be collected by solar panels on the lunar surface and beamed to any location in cislunar space [36,37]: The lunar solar power can convert the collected lunar surface solar energy to microwaves, and then the microwaves are transmitted directly or indirectly as multiple power beams, via

Table 2. Average concentrations of solar wind implanted volatiles in the lunar regolith [18].

Volatile	Concentration, ppm (μg/g)	Average mass per m^3 of regolith (g)
H	46 ± 16	76
^{3}He	0.0042 ± 0.0034	0.007
^{4}He	14.0 ± 11.3	23
C	124 ± 45	206
N	81 ± 37	135
F	70 ± 47	116
Cl	30 ± 20	50

orbital reflectors/re-transmitters, to receivers on Earth called rectennas [38].

In situ water replenishment methods

Thermal extraction of water from icy lunar soils

Water resource replenishments on the lunar surface not only are the most basic requirements for human survival but also can further realize the in situ conversion and supply of oxygen and hydrogen through photolysis or electrolysis technology, which can be used as the propellant for rocket launch and the in situ replenishment of oxygen for human survival. At the same time, water resources can also be used as important raw materials for Moon-based scientific experiments, lunar surface biological culture, lunar construction, radiation protection, etc. Therefore, the acquisition of in situ lunar water resources will be the most urgent technical requirement for future lunar exploration and base construction missions.

The existing reported results show that there are a lot of water resources at the poles of the Moon [39–41]. Most of the water resources are mainly contained within icy lunar soils in the PSRs at the South and North Poles. A conceptual scheme of solar-thermal mining of water from the icy soils in the PSRs at the lunar poles was shown in Fig. 2. In this scheme, the sunlight on the lunar surface is used directly as the heating source, and reflective mirrors were installed at crater edges to conduct sunlight to heat the mining drills or tents [42–44]. The ices in the frozen soils were heated to sublimate or evaporate, and then the water vapor was captured within the tent and collected by cold traps. Another promising water extraction method from icy lunar soils is the drill-based excavation systems [45–49]. This method mainly uses hollow auger to drill the icy lunar soil and then uses heating scheme to vaporize and collect the ice, so as to achieve the purpose of water resources development. For example, Zacny et al. [45,46] from the Honeybee Robotics developed a Planetary Volatiles Extractor, which is an integrated system combing a drilled-based excavation module with a volatile collecting module.

Biswas et al. [49,50] also developed an integrated instrument for icy soil drilling, gas extraction, and mobility analysis of lunar volatiles. The thermal vacuum test results showed that water has been successfully extracted from the icy lunar regolith simulant. The reported apparatus consists of a spiral drill shell and a central heating rod that can be inserted into the subsurface soils. Once inserted, the heating element would heat the packed icy soils, and the water vapor and other volatiles were released and detected by an ion trap mass spectrometer integrated in the apparatus. The size of the reported instrument is 120 mm × 120 mm × 400 mm with a total mass of 1.9 kg and a power consumption of about 20 W, respectively [49]. Recently, He et al. [47,48] proposed a consecutive auger-based water extraction and collection scheme from icy lunar regolith simulants. The technological process is that the auger-drill descends to the surface of icy lunar soils to form a temporary sealing space and then the auger-drill begins to drill holes to transport the icy lunar soils upward and heated by an infrared heating lamp. Then, the heated water vapor flows into a cold condenser to be collected.

Water production by hydrogen reduction of lunar soils

Because of the limitation of the distribution area of lunar water ice resources, it is difficult to realize the large-scale extraction and application of water resources from icy lunar soils. Therefore, it is necessary to develop a more widely feasible and reliable in situ water acquisition method to meet the demand of in situ water resource replenishment faced by future manned lunar exploration missions. Thus, another in situ water acquisition scheme based on hydrogen reduction of lunar soils has been widely developed. The reduction scheme of lunar soil is considered to be the most feasible technical scheme due to its mild reaction conditions, extensive source of raw materials, and mature technical conditions. The main reaction materials are the ilmenite ($FeTiO_3$) in the lunar soils and the basic reaction principle is as follows:

$$FeTiO_3(s) + H_2(g) \rightarrow Fe\,(s) + TiO_2(s) + H_2O\,(g) \quad (1)$$

According to the program of the Package for Resource Observation and in Situ Prospecting for Exploration, Commercial Exploitation and Transportation payload from the ESA, Sargeant et al. [51–53] developed a prototype for hydrogen reduction of ilmenite to produce water (Fig. 3). The verification tests of different samples such as lunar soil simulates (NU-LHT-2M), lunar meteorite samples (no. NWA12592), and Apollo 11 mission samples (nos. 10084 and 60500) have all achieved a certain degree of hydrogen reduction and water production. For the Apollo samples with high titanium content (sample no. 10084, ilmenite content of ~14.55%), the oxygen reduction mass percentage was about 0.94 ± 0.03%. For low titanium samples (sample no. 60500, ilmenite content of ~1.14%), the reduction mass percentage of oxygen element in lunar soil was about 0.18 ± 0.02%. For the implementation of the ROxygen project [54,55], researchers at the Johnson Space Center of NASA carried out a detailed verification experiment to investigate the hydrogen reduction of lunar soils to produce water, and the percentage of oxygen element conversion was about 1% to 2%. In addition, a large-scale scheme of in situ acquisition of lunar surface oxygen via the soil reduction method with a yield of 1,000 kg/year was also proposed. Other researchers from the Kennedy Space Center, Marshall Space Center, and Jet Propulsion Laboratory of NASA also carried out series of works on conversion and utilization of lunar soil. Their results reveal that hydrogen reduction of lunar soil is a promising solution for in situ water and oxygen replenishment [2,54].

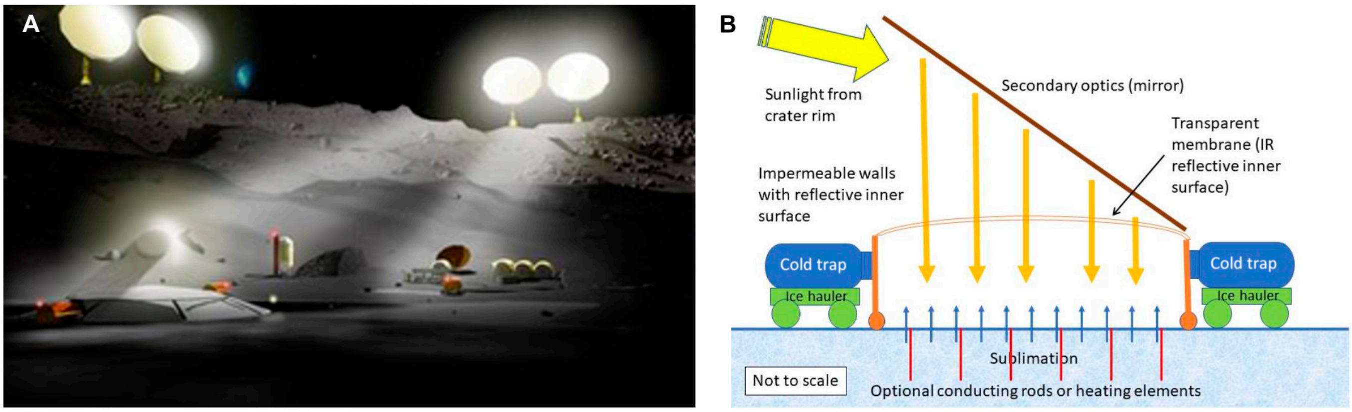

Fig. 2. The conceptual design of the solar-thermal mining of water resources from icy soils at the lunar poles [39]. (A) The schematic diagram of solar-thermal extraction of water from PSRs at the lunar poles. (B) The schematic diagram of thermal extraction process of water from icy lunar regolith. IR, infrared.

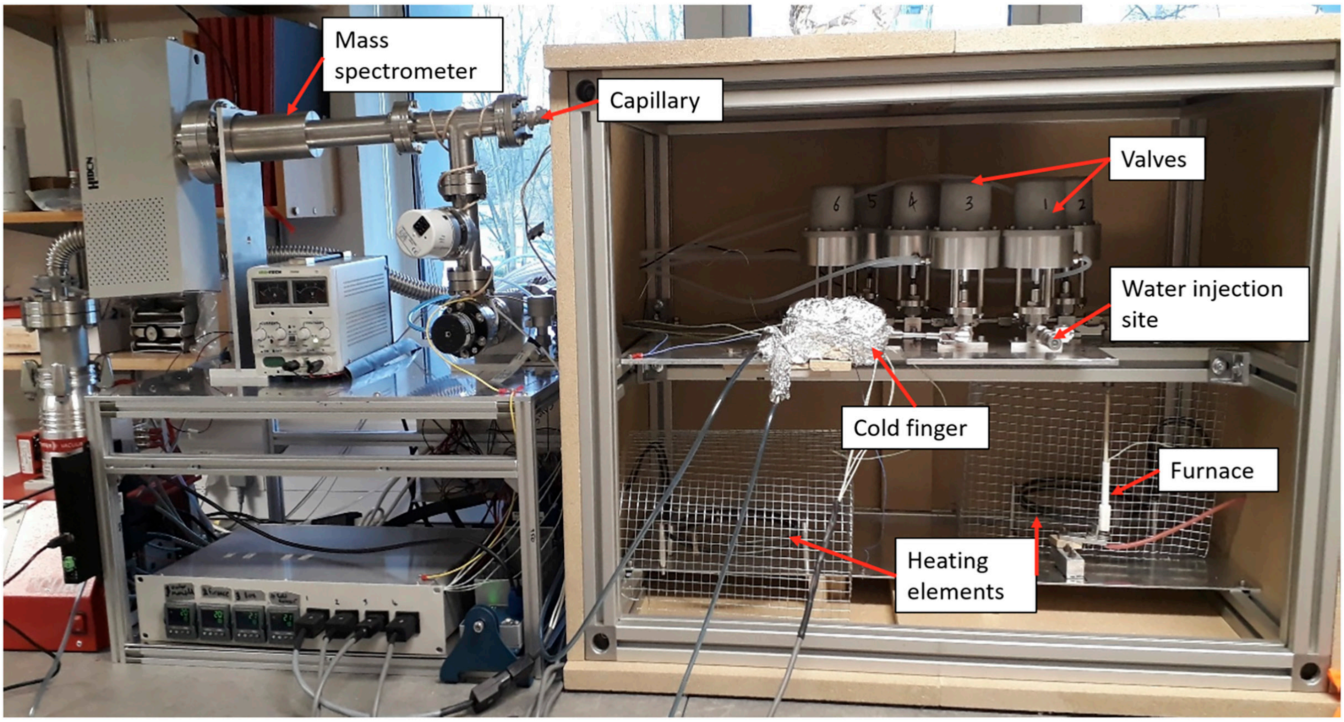

Fig. 3. Photographs of the prototype for hydrogen reduction of ilmenite to produce water [51].

As reviewed above, 2 different methods of in situ water resource acquirement have been widely investigated. The aforementioned 2 methods, namely, the water extraction from icy soils and the water production by hydrogen reduction, were respectively developed for completely different application scenarios. However, the present detection results show that the water/ice resources mainly distribute in PSRs at the lunar poles. Because of the limitations of the distribution area and the difficulties of energy accessing, it is impossible for the global application of water replenishment by the method. The water extraction method from icy soils would be more suitable for the in situ water replenishment for lunar bases in the polar regions. Nevertheless, the water production method by hydrogen reduction would have a wider application prospect due to the widespread of lunar soils. Meanwhile, there are still several technical problems such as high energy consumption, excavation, and beneficiation of minerals that need to be solved.

In situ oxygen preparation methods

Extraction of oxygen from lunar regolith can provide fuel replenishment on the lunar surface and maintain life support systems, while the remaining metal elements can be applied in manufacturing and construction. As mentioned above, oxygen can be further extracted from the water resources achieved by the above 2 methods. Here, other methods for directly extracting oxygen from lunar regolith are briefly reviewed by describing the general reaction principles, reaction device design, and the current situation of the research.

Electrolytic reduction method

In the process of generating oxygen by electrolytic reduction, metal elements in the lunar regolith are deposited at the cathode by reducing, while oxidation takes place at the anode where oxygen arises. This article introduces 2 concepts of reduction via electrolysis, including molten regolith electrolysis (MRE) and molten salt electrolysis (MSE). The MRE method, which seems to be the most direct method to achieve oxygen and metals on the Moon, requires no additives or consideration of recycling products but rather performs direct electrolysis on the original molten lunar regolith [56]. The oxygen anions in molten lunar regolith move toward the anode where oxygen evolves, while metal cations move to the cathode where metals deposit (Fig. 4).

The process of silicate electrolysis reduction of iron oxide was first patented by Aiken [57] and had been widely applied in the metallurgical field. Compared with other oxygen production methods, the MRE method is able to achieve oxygen extraction yields (kilograms of oxygen per kilogram regolith) on the order of 15% at low operating temperatures, while at high operating temperatures, this value can be increased to around 37.5%, which has lower energy consumption and higher resource utilization [58]. At the same time, the alloy produced by MRE could be used in the construction of infrastructure on the lunar surface. The temperature of direct electrolytic melting of lunar regolith was relatively high, reaching nearly 1,600 °C, resulting in a short service life of anode materials made of iridium with a consumption rate of ~7.7 mm/year [59,60]. However, Kim et al. [61] explored the durability of inert anode according to the mineral composition of melt, finding that the corrosion rate of inert anode iridium decreased with the higher content of silica in the melt.

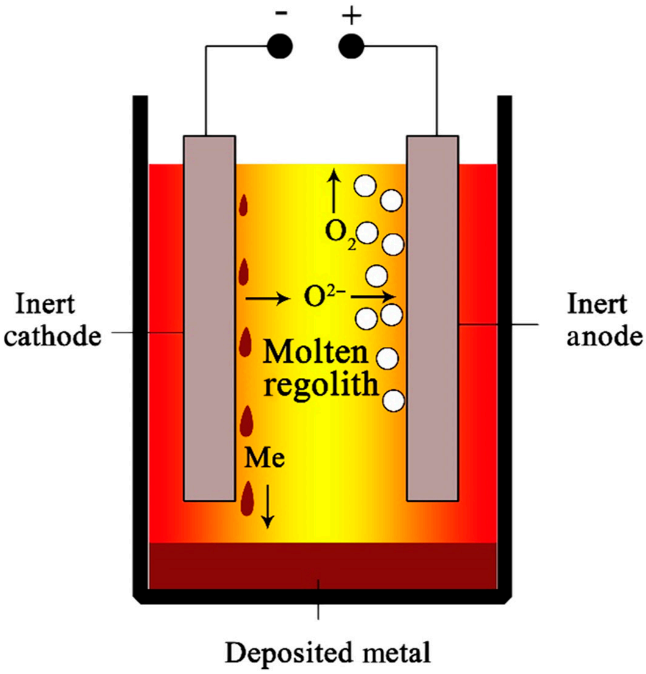

Fig. 4. MRE process.

The MSE method of solid lunar regolith is derived from the Metalysis Fray Farthing Chen (FFC) Cambridge process for the electrodeoxidation of metals and metal oxides [62]. There are 2 different principles of MRE from this reaction, of which the oxide reduction takes place within the cathode entirely in the solid state, while the molten salt electrolyte is not consumed. An electrolytic cell is adopted in the FFC process typically operated at temperatures of around 900°C where the calcium chloride ($CaCl_2$) electrolyte is molten and the oxygen contained in the sintered metal oxide cathode is ionized [23]. The oxygen anions transported toward the anode are oxidized, forming O_2 gas. The cathode is depleted of oxygen and gradually reduced to finally comprise pure metal or alloy only [63]. To avoid high energy consumption and deterioration of materials used in the electrochemical cell, Meurisse et al. [64] reduced the temperature of the FFC process by altering the salt from pure $CaCl_2$ to eutectic mixtures with KCl, NaCl, and LiCl with an oxygen-evolving anode made of SnO_2, which showed at least 40% of the oxygen extracted from lunar minerals in 24 h at temperature as low as 660 °C. However, during the FFC process, calcium stannate ($CaSnO_3$) phase is found to precipitate on SnO_2 electrodes, which is denser than SnO_2, but weight change of anode is not evident. Because of its insulating property, calcium stannate coating on the SnO_2 electrode may affect the electrolytic reaction process in the long term [65].

In summary, the process of MRE can be widely used in all types of lunar regolith, while investigating more durable electrode materials is the key to ensure the progress of the reaction. During the high-temperature melting process, volatile compounds in the lunar regolith are likely to release chlorides or metal vapors, which must be purified from the gas resource for safe supply [58]. In addition, for the MSE method, the oxide powder feed materials need to be subjected to a complicated pretreatment including the pressing of tiles and the sintering into compact oxide bodies. Because of the porosity of the solid metal product, a quantity of electrolytes is consumed from the cell during the process. Thus, the MSE method requires the replenishment of fresh salt from Earth [23].

Vacuum thermal decomposition method

The vacuum thermal decomposition method directly heats the raw materials under vacuum conditions to decompose the oxide in lunar regolith into oxygen elements and other constituent elements. Different from electrolytic reduction, thermal decomposition only requires thermal energy and does not need other auxiliary materials. The schematic diagrams of the vacuum thermal decomposition method are shown in Fig. 5. Several different methods of heating the lunar regolith simulants to the required temperatures were adopted in the vacuum thermal decomposition method. However, the thermal decomposition of silicon oxide into oxygen and silicon requires more energy than other magnesium and iron oxides in the lunar regolith. Therefore, Li et al. [66] used silicon dioxide as the raw material for the laser heating-induced thermal decomposition under a vacuum to generate SiO_x (x ranges from 0.12 to 1.74) and oxygen. As metals and oxygen are collected in the gaseous environment, gaseous metals should be condensed immediately before rebinding with oxygen, which must be continuously excreted from the system to maintain the vacuum state of the reaction process.

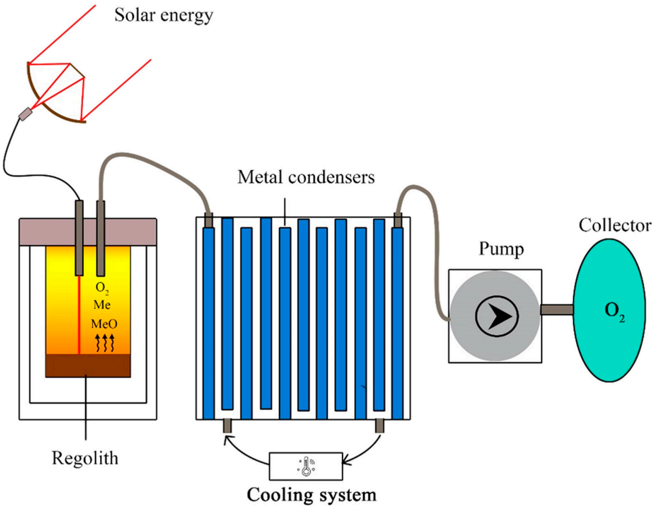

Fig. 5. Vapor phase pyrolysis process.

In summary, a group of oxygen extraction methods from lunar regolith have been demonstrated in the laboratory. However, there are still several key problems to be investigated carefully before these methods are put into application. Specifically, the process of electrolysis of molten regolith does not need any additional electrolyte, but it has high requirements for the inert electrode. The method of electrolysis in molten salt consumes large amounts of salt medium, which should be provided frequently that is more likely to affect the system of its volatility as halides. The vacuum thermal decomposition method requires heat-resisting material to sustain the reaction. Thus, the research and development of alternative ISRU processes for extracting oxygen from lunar regolith remain a crucial and relevant area for future lunar exploration.

Silicon, metal, and fiber refining from lunar soils

Silicon is one of the most abundant elements in the lunar soils [3,67]. Most of the silicon elements exist in the form of silicates on the Moon. Nowadays, purified silicon is widely used in solar cells because of its semiconductor properties. On the lunar surface, the energy density of solar radiation is about 1,370 W/m^2 compared with the 950 W/m^2 on Earth [68]. The conversion and application of solar energy would be the most important in situ energy acquirement scheme for future Moon exploration missions. On the lunar surface, one of the reported silicon production processes is to heat the lunar regolith in the presence of reductants such as fluorine. The fluorine will supersede the oxygen elements in the silicate, and silicon elements are produced in the form of silicon tetrafluoride. Then, the plasma deposition processes and chemical vapor deposition processes are also used to produce pure silicon for solar cell applications [67]. Another silicon production method is the typically carbothermic reduction of silicates at the heating temperature of about 2,000 °C to melt the silicates to a purity grade of 98% [67]. Furthermore, a Metalysis FFC electrolytic method is developed to extract metallurgical grade silicon (purity grade > 99%) with much lower energy consumption [67,69].

There are a lot of metal oxides in lunar soils. Extractions of these metals would be of great significance in lunar construction, lunar-based scientific experiments, and lunar in situ manufacture. Carbothermal reduction, hydrogen reduction high-temperature MSE, and vacuum thermal decomposition have been tried to extract metal from lunar soils, respectively. The hydrogen reduction method has been discussed above. The carbothermal reduction and MSE methods are briefly reviewed in this section. The carbothermal reduction method uses carbon as a fuel and reducing agent to reduce metal oxides to metals at high temperatures [70,71]. Sen et al. [70] realize an extraction and refining of metals by heating mixtures of lunar regolith simulant and graphite powder to about 1,500 °C. Balasubramaniam et al. [71] discussed the chemical conversion model of the carbothermal method to evaluate the production rates. Their model assumed that the methane would pyrolyze into elementary carbon and hydrogen when it makes contact with the molten surface of lunar regolith particles. Then, the deposited carbon particles mixed in the molten lunar regolith and reacted with metal oxides in a reduction reaction.

On Earth, basalt fibers have been widely used as matrices of composites, such as in the construction industry, bridge industry, and concrete structural members. The continuous basalt fibers are expected to replace the metal brackets, which could not only improve the mechanical properties, ductility, and high temperature resistance of the structure but also solve the problem of corrosion resistance of the traditional materials [72,73]. A large number of basalts have been detected in the lunar soils. Thus, the fabrication of basalt fibers would play key roles in lunar construction, in situ manufacture, environmental control, and life support [74]. As shown in Fig. 6, Xing and colleagues [73,75] designed a 2-step method for the preparation of continuous lunar soil fibers. The raw material of their work for lunar soil fibers was a kind of lunar soil simulates (CSA-1) [76]. The tensile strength of their fabricated continuous fibers was as high as about 1,400 MPa [73]. Becker et al. [77] further developed a concept of a fiber spinning facility for in situ large-scale preparation and application of fibers on the Moon.

As reviewed above, metallurgy and mineral refining of lunar soils have been widely investigated by numerous verification experiments on Earth. However, there are still several technical problems to be solved before the in situ application of these technologies on the Moon. Specifically, on the one hand, the mining and beneficiation of lunar minerals are the basic premises of all the above technical schemes. Thus, efficient collection and beneficiation of lunar minerals should be carefully investigated for future missions. On the other hand, all the above technical schemes require a large amount of thermal or electrical energy. The energy in situ replenishment technologies will play key roles in the development of the above schemes. In addition, selections of reducing agents and technical processes would determine the purity of products, cost of technology, and other properties. Furthermore, several technical steps are highly complex and may involve precision control requirement; thus, they are not suited to the in situ lunar application. Therefore, in-depth theoretical and experimental research should be carried out for future lunar exploration missions.

In situ lunar construction techniques

The in situ construction of the lunar base is of great significance for the long-time survival of human beings on the Moon. Using local materials from lunar resources to realize in situ construction is a feasible method. The entire Moon surface was covered with lunar regolith [78], and the mineral composition is similar to that of basalt ore distributed on Earth's surface

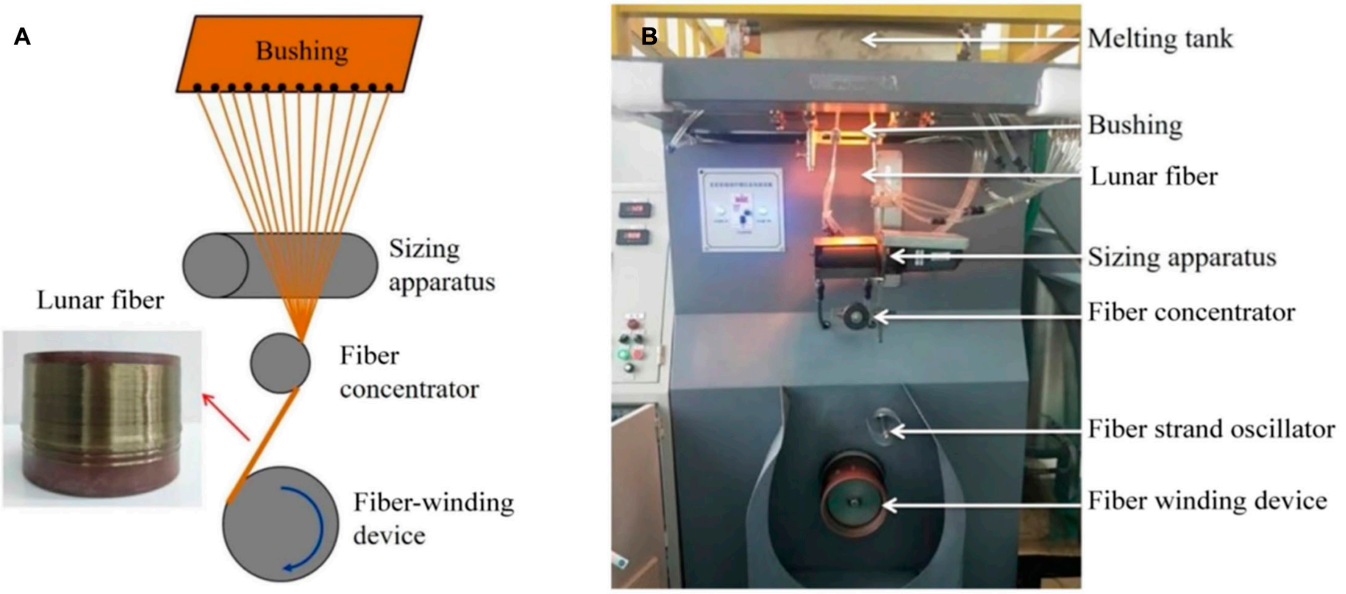

Fig. 6. Preparation method of continuous lunar soil fibers. (A) Schematic diagrams and (B) photographs of the equipment for preparation of lunar soil continuous fibers [73].

[79–83]. Because of the extreme lunar environment, such as high vacuum and low gravity, the common methods for Earth construction are not suitable for the Moon. Therefore, various construction methods using lunar soil based on ISRU have been proposed. According to the different construction ways and materials, the construction shaping methods applied to lunar soil include additive manufacturing (AM) techniques of lunar soils, sintering techniques of lunar soils, and extrusion printing techniques of lunar regolith inks.

AM techniques of lunar soils

AM, more commonly known as 3-dimensional (3D) printing, is referred to the process of joining materials to make objects from 3D models. AM technologies have been widely studied for building in situ lunar regolith into 3D objects, which use premixed pastes composed of lunar soil simulant and liquid binders as the printing material to construct lunar 3D objects layer upon layer [84,85]. At present, various proofs of concept combined with the 3D printing technology and lunar regolith as raw materials have been proposed to support lunar construction, such as contour crafting and D-Shape method.

Contour crafting (Fig. 7) is a gantry-based 3D printing technique that uses liquid-state binder to crystallize materials rather than heating and sintering them [78]. Materials such as sulfur concrete are extruded against a nozzle, and the extruded material is smoothed by robotic trowels to directly build 3D objects layer upon layer [86,87]. Contour crafting was selected by NASA to explore the potential of constructing one reliable and quick lunar infrastructure for its convenience of construction without interlayer bonding problems [88,89]. However, pumping with a contour crafting printer is not possible under a vacuum condition. In addition, it is difficult for contour crafting to print a shallow arch because such arches must be printed horizontally by the contour crafting on the plane and raised to an upright position by a robot afterward [90].

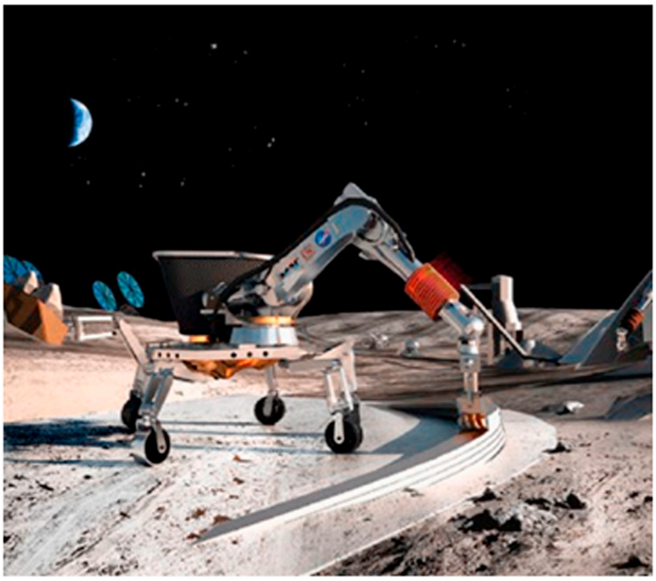

Fig. 7. NASA contour crafting robotic fabrication technology attached on a lunar rover [93].

ESA developed D-Shape 3D printing technology to produce in situ constructions on the Moon using lunar regolith as raw materials [91,92]. The D-Shape method is suitable for large-scale construction in a single process and provides a feasible solution for the direct construction of outer protective shells for lunar habitats in any shape. Nevertheless, the D-Shape program still has the following drawbacks. First, the injection of fluids under low gravity or vacuum is problematic [93]. Second, the huge printer and an excessive amount of material including liquid ink must be transported from Earth to Moon, which costs a lot [93,94]. In addition, the D-Shape method requires the screening process of the lunar soil to have powdered materials.

Sintering techniques of lunar soils

The sintering process heats the fine grains of metallic or ceramic material to the melting temperature to form a fixed shape. In this process, microwave and concentrated solar light heating methods have been developed for lunar soil sintering, respectively. Microwave sintering, which has been proposed as an alternative to radiant furnace sintering [95], is a technique for in situ sintering of molten lunar regolith on the lunar surface using microwave energy. Microwave sintering has unique advantages over conventional heating such as high efficiency, even heating, and energy availability. Taylor and Meek [96] conducted microwave sintering experiments with the real Apollo 17 soil, and the result demonstrated that the formability and strength of the sintered product were significantly improved. Because of the limited amounts of real lunar soils collected from the sampling return mission, recent studies [87,97–103] mainly focus on microwave sintering techniques combined with lunar simulants such as the JSC-1A, JSC-2A, and CLRS-1 samples, which prove that the above mentioned lunar simulants have a good performance of microwave surface heating. Researchers at Jet Propulsion Laboratory [104] have described the conceptual approach to supporting NASA regolith construction research. Nevertheless, the high vacuum environment of the Moon would lead to a considerable impact on the sintering processes and the characteristics of the sintered products [105]. Thus, there is a need to conduct microwave sintering of lunar regolith under vacuum conditions in the future.

Solar sintering of regolith [106] via directly obtained and concentrated solar light on the Moon to sinter the lunar regolith would be a viable construction technique as solar energy is limitless and readily available on the lunar surface [78]. Hintze et al. [107] developed a solar sintering technology for dust mitigation, which used a mobile Fresnel lens to concentrate sunlight on the top layer of the lunar regolith for sintering treatment. Researchers also have investigated the potential utilization of solar sintering methods in the AM technologies. By combining concentrated sunlight with a 3D printing process, basic bricks [108], small structural components used for the in situ fabrication of microtruss structures for construction structures [109], and interlockable building elements would be produced from lunar regolith simulants. In addition, Fateri et al. [110] also optimized the process parameters of sintered regolith under vacuum conditions to obtain better AM results. Despite the advantages, solar sintering methods still have the following limitations. First, the depth of the solar sintering process by the solar concentrator is limited compared to the microwave sintering treatment. As a result, it takes much longer time to fabricate than microwave sintering [107,111,112].

Extrusion printing techniques of lunar regolith inks

Up to now, it is still not very realistic to build large structures using only lunar soil. In addition, the common 3D printing method on the Moon is usually limited by shaping processes and material characteristics, and it cannot be fully applied on the lunar surface with insufficient resources [79,113]. Therefore, the extrusion printing method of lunar regolith inks has attracted extensive attention from researchers due to its wide range of applications. In 2018, Taylor et al. [109] described the microstructures and mechanical properties of regolith cellular structures produced via liquid inks containing JSC-1A lunar regolith simulant powders (Fig. 8). They found that air-sintering will introduce higher relative densities, linear shrinkages, and peak compressive strengths.

In addition to the poly(lactic-*co*-glycolic acid)copolymer binder in the inks, photocurable resins are also an excellent modification assistant. In 2019, Liu et al. [114] prepared the printing slurry by mixing CLRS-2 lunar regolith simulant powders with photocurable resins, and it exhibits excellent printability. The average compressive strength of the samples is 428.1 MPa, and flexure strength is 129.5 MPa, which are higher than those reported researches previously. These improved mechanical properties could be due to the small average diameter of pores and the chemical compositions. Combined with the advantages of the AM process, the digital light processing fabrication method will bring a quantitative capacity for moon base construction in the future.

In situ energy conversion and utilization techniques

For long-term human activity on the Moon, one of the greatest challenges is the conversion, storage, and utilization of in situ energy. An ISRU approach as a means of energy provision is to use the lunar regolith as the medium for thermal energy storage (TES). Heat can be stored in solid materials (thermal mass) in a sensible form, and the thermal mass can be kept at a high temperature until the energy is released using the reverse mechanism, which can be used as the source for a heating system [115,116]. In the in situ energy utilization on the Moon, there are 2 different kinds of systems to produce heat and electricity using lunar regolith. As proposed by Climent et al. [117], the first system uses thermal wadis made of lunar regolith to supply enough heat to keep lunar devices above their minimum operating temperature. In the second system, a heat engine is activated using solar power and simultaneously heats a thermal mass during daylight, and this thermal mass is used as a high-temperature source to run the heat engine during the night. Nevertheless, the properties of native lunar regolith are regarded as very poor when it comes to energy storage and it contains the elements needed to be converted into a reasonable thermal conductor.

To improve the efficiency of lunar regolith in energy utilization, Fereres et al. [118] explored the design of a packed bed TES system using regolith as the storage medium through a numerical model. Different heat transfer fluids are evaluated for the TES charge/discharge, using medium available from other complementary ISRU processes or gases indispensable for a life support system. Notsu et al. [119] proposed a lunar long-duration method that uses a characteristic of very low thermal conductivity of lunar regolith. A heater is put into the desired depth of the regolith and heats up the regolith layer during lunar daytime (Fig. 9). Because of the very low thermal conductivity of regolith, stored heat in regolith propagates gradually and raises the surface temperature during the cold lunar night.

The stored energy of lunar regolith can not only provide means of temperature control in the lunar light but can also be transported to electric energy, and relevant research is also plentiful. Figure 10 shows the proposed model for the energy storage and electricity generation system proposed by Climent et al. [117]. The energy collected by the solar collector is transported to the Energy storage subsystem and, when it is needed, to the heat-to-electricity conversion unit.

On the basis of the above method, Lappas et al. [120] proposed a system using a sun concentrator/heat/pipes and a radiator enhanced/extended with the Prometheus thermoelectric

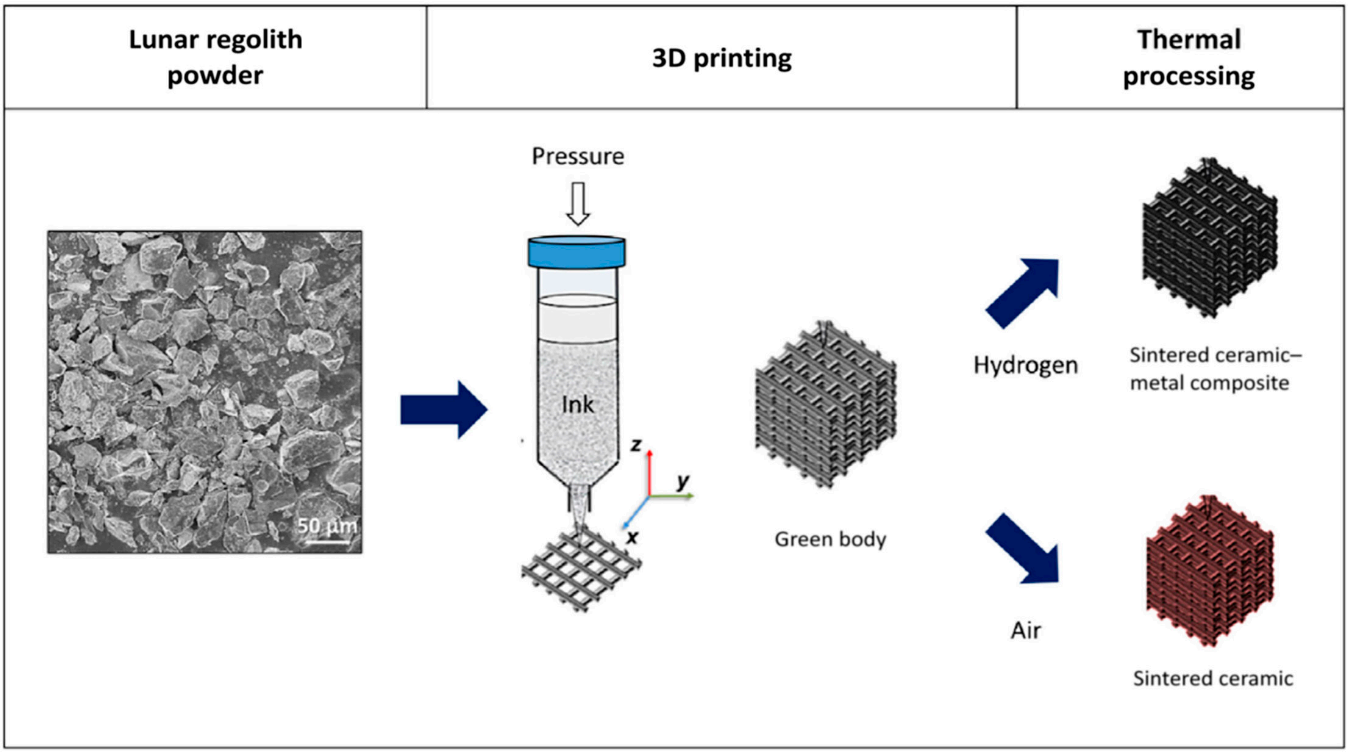

Fig. 8. Schematic of the 3D fabrication process for lunar regolith cellular structures [109].

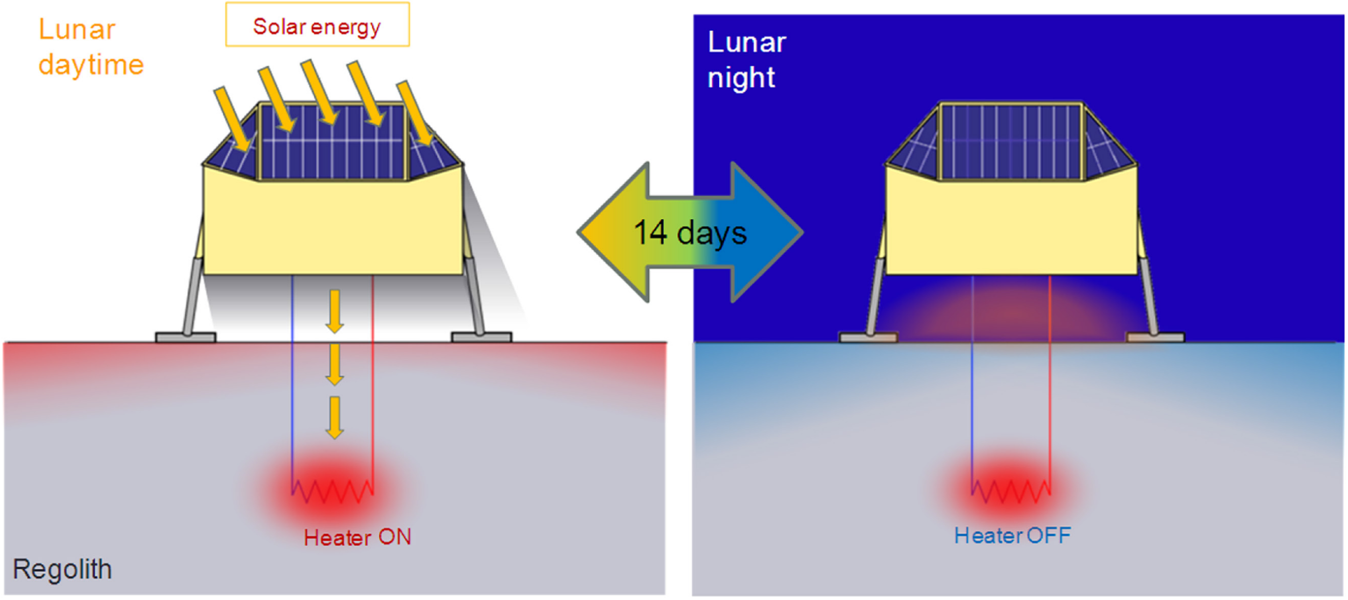

Fig. 9. Schematic view of the proposed method by Notsu et al. [119].

generator for simultaneous heat storage and power generation. They extended the existing thermal wadi concepts and proposed a novel thermoelectric generator that uses temperature differential to generate electric power on the Moon. Their experimental data show that the 20-kg thermoelectric generator prototype can generate a 6- to 11-kW region using the simulated temperature gradient from a thermal wadi/sintered regolith, thus showing the feasibility of producing in situ electric power and storing heat at the same time to protect space assets on the Moon. Lu et al. [121] theoretically analyzed a lunar-based solar thermal power system with regolith thermal storage consisting of solar concentrator, regolith thermal reservoir, and Stirling generator [121]. They analyzed the influencing factors on the output power and efficiency of the system and discovered that the thermal storage effectiveness of lunar regolith is relatively low because the native regolith is a poor thermal mass material due to the high porosity. Hu et al. [122] designed a closed-loop system of thermal energy reservoir (TER) using

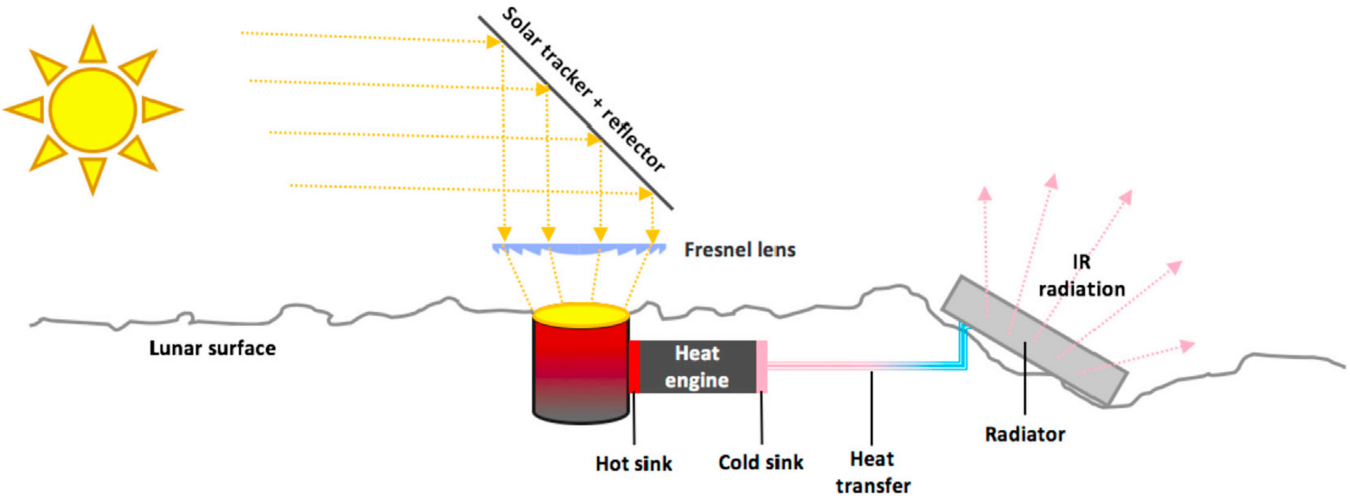

Fig. 10. TES system coupled with a heat engine and a radiator [142].

stacked regolith spheres and fuel tanks and numerically analyzed the thermal storage characteristics of the system. They simulated the transient temperature profile of TER using the porous medium model under different regolith sphere diameters and pump pressure, thus obtaining the thermal storage capability of TER. Xie et al. [123] proposed a conceptualization of lunar-based in situ energy support technology using the temperature difference to generate electricity. They proposed 2 methods of power generation using lunar regolith: lunar thermoelectric materials thermovoltaic power generation system and lunar magnetic levitation power generation system. The lunar thermoelectric material thermovoltaic power generation system directly used thermoelectric materials to realize thermoelectric conversion.

For long-term human lunar surface activities, the in situ utilization of lunar regolith for energy conversion and utilization is quite crucial and indispensable. According to the analysis of the above literature, various schemes have been proposed for the energy utilization of lunar regolith, and numerical simulation and experimental research are implemented to optimize the schemes. The key issues to further promote the development of lunar energy utilization include (a) the process of regolith to improve its heat storage property, (b) the optimization of the material parameters to improve the heat-to-electricity conversion property, and (c) the engineering design of the energy utilization payload adapted to the extreme environment of the lunar surface.

Artificial ecosystem for lunar life support

Long-term manned exploration on the lunar surface requires a large number of survival materials, and that is unrealistic to completely rely on supplies from Earth. It is urgent to in situ solve key problems such as oxygen/water regeneration, food production, and waste recycling. Building an artificial ecosystem is the most advanced method to achieve ISRU and survival materials recycling. Engineering technology and ecological theory are applied to achieve energy flow and material circulation among plant, animal, and microbial units, and there have been varied related research.

Since the 1960s, researchers in the Soviet Union/Russia exploringly cultured microalgae for oxygen regeneration in an artificial ecosystem and then added plants to the system, which obviously improved the gas and water regeneration rate [124]. They attempted at building a system to acquire a higher material cycling rate, which was named BIOS-3, and several crewed experiments were carried out in it. The results showed that more than 90% of gas and water requirements were met because of the 63-m^2 planting aera [125,126]. Americans began research on artificial ecosystems almost at the same time. In the 1980s, NASA developed the Environmental Control and Life Support System and put forward the theory of Advanced Life Support for missions such as lunar and Martian bases [127]. On the basis of previous research, NASA carried out the Lunar–Mars Life-Support Test Project in the late 1990s. Biological regenerative life support technologies were integrated with traditional physical/chemical technologies, and the plant met 25% oxygen and 5% food requirement [128]. In Europe, the Micro-Ecological Life Support System Alternative was started in 1989 and was integrated with several compartments: waste decomposition compartment, photosynthetic heterotrophic food production, nitrification compartment, photosynthetic food production, and atmospheric regeneration compartment and the crew compartment; the compartments are being designed and unit research will be carried out with the efforts of many European countries, research institutes, and companies [129,130]. The optimal structural design of a lunar greenhouse module was studied by the German Aerospace Center, and a semicylindrical hybrid structure with rigid endcaps (20 m in length, 3 m in radius, dry and edible biomass yield of 22 kg/month.) was proposed [131].

In China, the China Astronaut Research and Training Center established a small ecosystem in 2011 and completed a short-term crewed closed experiment with 2 people for 30 days on 1 December 2012. Later, a large Earth-based experimental facility was built with the cooperation of other institutes, and then they conducted the "Space 180" experiment in 2016, involving 4 crew members, lasting 180 days. The "Space 180" experiment achieved a 100% regeneration of oxygen, a 99% regeneration of water, and a 70% regeneration of food and got research achievements in medicine [132] and material circulation [133]. In 2013, China's first Earth-based large-scale crewed comprehensive experimental BLSS system "Lunar Place 1" was built by L. Hong's research team at Beihang University, including a plant cabin and an integrated cabin, with a total area of 100 m^2, a total volume of 300 m^3, and a planting area of 69 m^2. In 2014, China's first crewed high-closure closed experiment was carried out in Lunar Palace 1, lasting for 105 days. Three crew members cultivated 21 types of grain and vegetable crops, cultivated yellow mealworm using biologically treated straw, and treated waste from all members inside the system, achieving a 100% regeneration of oxygen, a 100% regeneration of water, and a 55% regeneration of food [134]. In 2016, Lunar Palace 1 completed the technological upgrade, with 2 plant cabins and 1 integrated cabin, a total area of 160 m^2, a volume of 500 m^3, and a planting area of 120 m^2 as Fig. 11. The "Lunar Palace 365" experiment was conducted from 10 May 2017 to 15 May 2018, lasting for 370 days [135]. The crew cultivated 35 kinds of plants, including grain, vegetable crops, and berries. The plant production met 100% of the crew's need for plant food. Wastewater, urine, feces, and plant straw were also recycled. The experiment achieved a 100% regeneration of oxygen and water and an 83% regeneration of food under the load of 4 crew members.

As one of the core units of the artificial ecosystem on the Moon, plant units require a large number of substrates in situ. Lunar soil can be used as the substrate for plant cultivation. However, lunar soil's properties, such as small particle size, low porosity, high bulk density, poor water holding capacity, and no organic matter, make it not conducive enough to plant cultivation as a substrate. NASA researchers conducted plant cultivation experiments using lunar soil samples collected during several lunar missions (Apollo 11, 12, and 17). The results showed that the direct use of lunar soil for plant cultivation would lead to ionic stresses thus a significant decrease in growth indexes and quality [136]. Therefore, lunar soil needs to be improved to form a substrate with similar properties to Earth soil for plant cultivation. It is the main technical route to improve lunar soil by adding organic matter and microorganisms to imitate the biological weathering experienced by Earth soil. A conceptual study to grow plants for a permanently manned lunar base proved that a microbial community could support the growth and development of the pioneer plant in a substrate of low bioavailability like lunar

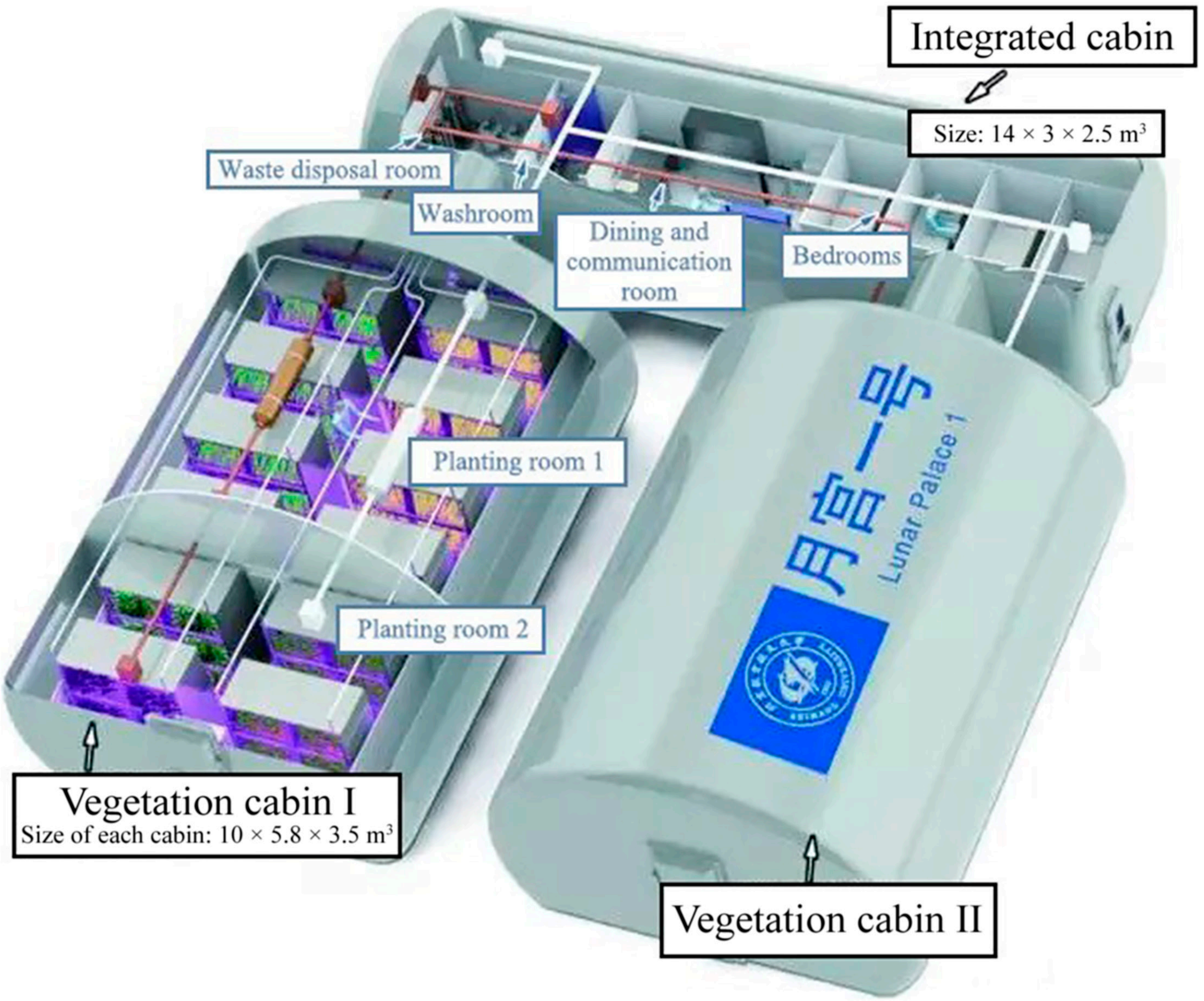

Fig. 11. The constructure of Lunar Palace 1 [134].

soil [137]. The addition of compost and shredded rye leaves improved the growth of plants grown in simulated lunar soil, but not as much as in Earth soil [138]. The Lunar Place 1 team at Beihang University used organic solid waste (plant residues, human feces, and microorganisms) mixed with simulated lunar soil to improve these physical and chemical properties. The seedling length of wheat cultivated in simulated lunar soil was only 25% of that in vermiculite cultivation, and the initial improvement process increased the seedling length to 65% of that in vermiculite cultivation, which still needed to be optimized. Moreover, the remarkable increase in sodium ions during the improvement process indicated that biological weathering corroded the particles of lunar soil [139].

Development Requirements and Recommendations for Future Lunar Exploration Missions

As reviewed above, numerous research works have been reported to explore the ISRU schemes on Moon. These reported results include the in situ replenishment of water, oxygen, habitats, silicon, metals, fibers, foods, and energy on the lunar surface for future Moon exploration missions. Various methods for ISRU have been proposed and their technical characteristics, economic performance, and application scenarios have been discussed. Of course, with the progress of technology, these methods may upgrade greatly. Present ISRU methods are mainly based on the lunar soil on the Moon's surface (no more than a dozen meters generally), and it should be considered that some minerals are difficult to utilize and enrich with existing technical means, such as spinel and some rare metals. However, according to development roadmaps for future lunar exploration missions, including China's ILRS, manned lunar exploration missions, and NASA's Artemis programs, we suggest that the focus and direction of future development on lunar ISRU should give full play to the influence and role of the following aspects:

1. The requirement of survival matters including water, oxygen, and food should take priority over other matters and technologies.
2. Target areas of detection and base construction would play key roles in the selection of methods for the in situ acquirement of survival matters.
3. According to the mass and energy flows of different ISRU methods, technical feasibility and economy will be the main evaluation index.
4. A clear development plan should be formulated in phases to achieve the gradual goals within different time frames according to the roadmaps of lunar exploration missions.

Given these aspects, we recommend that the following technology schemes should give priority to development for the in situ acquirement of survival matters. As shown in Fig. 12, efficient mining technology should be the first to be broken through for sufficient access to raw materials. At the polar regions of the Moon, the icy lunar soils should be excavated from PSR for water extraction and plant cultivation via the in situ solar heating method. Then, the water could be further decomposed to oxygen and hydrogen by in situ photolysis or electrolysis technology. In this way, the key survival matters could be in situ replenished for the polar permanent future lunar bases. Liu et al. [140] estimated that the energy consumption for the water extraction from icy lunar soils ranges from 8.6 to 37.9 Wh/g, depending on the water ice contents and temperatures of icy lunar soils [140]. However, at the other regions of the Moon, only the dry lunar soils could be collected and used. The separation and beneficiation of ilmenites within the lunar soils provide extensive raw materials for hydrogen reduction to produce water on the whole lunar surface. Then, the water resources can be further used for plant cultivation and oxygen/hydrogen production. In addition, the decomposition of dry lunar soils could also directly produce oxygen along with relatively high energy consumption. The energy consumption for water production by the hydrogen reduction of lunar soils is estimated to be about 4.67 Wh/g [141].

According to the roadmaps of China's future lunar exploration missions including the phase IV of China Lunar Exploration Program (Chang'E-6, Chang'E-7, and Chang'E-8 missions), ILRS, and manned lunar exploration missions. Our recommendations

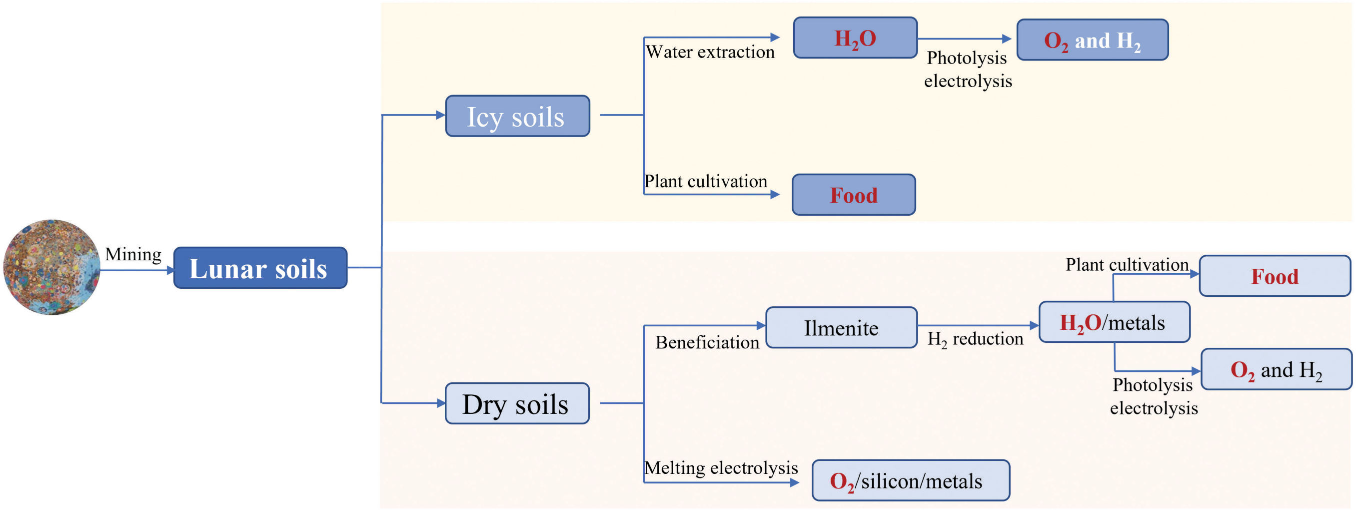

Fig. 12. Recommendations of technology schemes for the in situ production of survival matters.

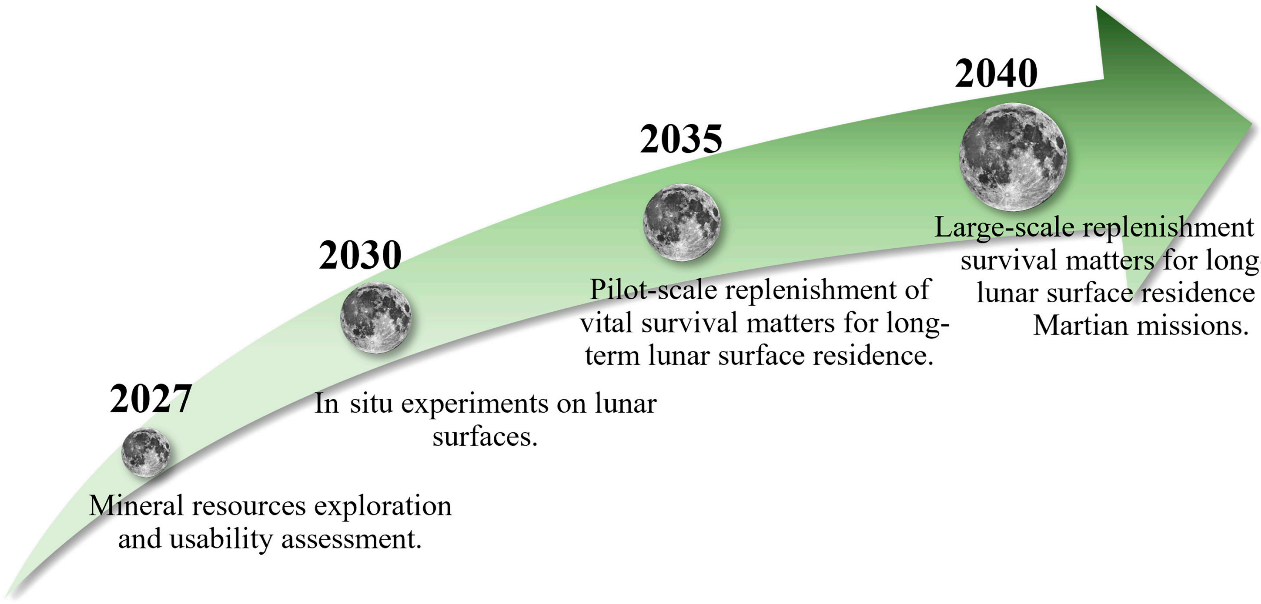

Fig. 13. Recommendations of roadmaps for future ISRU technology on the Moon.

of roadmaps for future ISRU technology on the Moon are shown in Fig. 13. The ultimate goal of the ISRU technology is to realize the large-scale replenishment of survival matters for long-term lunar residence and future Martian missions around 2040. Before the destination, we suggest a 3-step development plan in the next decade. In the first stage, basic scientific problems, technical issues, and technological solutions relating to the lunar ISRU should be sufficiently investigated. In addition, on this basis, the exploration and usability assessment of mineral resources should be first completed before 2027. The second stage, it will focus on the development of experimental payloads that can adapt to the lunar environment. Then, the in situ experiments on lunar surfaces could be directly carried out by payload experiments of lunar exploration missions around 2030. In the last stage, the facilities for lunar ISRU would be constructed and the pilot-scale replenishment of survival matters for medium-term lunar surface residence, and scientific activities would be realized around 2035. Finally, around 2040, large-scale replenishment of survival matters for long-term lunar missions and future Martian missions will be realized. In this way, the cost, reliability, and security of future lunar exploration missions and other deep-space missions will be improved. Thus, the lunar ISRU technology will contribute to the development of sustainable deep-space exploration missions.

Conclusion

Nowadays, China's lunar exploration project has completed the 3 steps strategy of "orbiting, landing, and sample return". China's future lunar exploration program will focus on establishing a permanent lunar station and carrying out long-term lunar surface scientific activities. The lunar ISRU technologies will play key roles in in situ replenishment of survival matters, in situ construction of lunar habitats, and in situ acquirement of energy in future lunar exploration missions. In addition, it will also be the premise for mankind to go further into deep space and develop sustainable deep-space exploration technology. Here, we provide a detailed overview of the recent progress on the lunar ISRU technologies in several aspects including the detection of lunar resources, in situ replenishment of survival matters, in situ construction of lunar habitats, and in situ utilization of lunar energy. Furthermore, we also propose recommendations of priorities for ISRU technologies and roadmaps for future development. We suggest that 3-step development plan should be fully carried out in the next decade before achieving the ultimate goal of the ISRU technology around 2040. This review article will provide a potential guidance for China's future lunar exploration missions.

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Data Availability

The data of this study are available from the corresponding author upon request.

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