Biofuel Production Via in Situ Resource Utilization on Mars

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Abstract. This paper is based on the fundamentals and principles of materials science and resource utilization. In-situ resource utilization (ISRU) can make full use of materials in space to produce the resources needed for human survival and even interstellar migration programs. Bio-based biofuel production solutions can address human consumption in space exploration while allowing the production of fuels in a sustainable manner, with minimal inputs and producing cleaner, more environmentally friendly fuels. ISRU biofuel production can be achieved by directly converting inorganic carbon (atmospheric CO2) into target compounds as biofuels by autotrophic microorganisms, or by fixing carbon and then use metabolic engineering to convert biomass or complex substrates into target compounds, completing a two-step biofuel production process. In this paper, we investigate a potential microbial cell factory for biofuel production on Mars via ISRU, leading to some relevant breakthroughs and discoveries. This paper advances the development of the research content through a series of studies. In this paper, we have studied and optimized the use of new energy fuels based on basic fuel performance studies. This paper provides a new way of thinking and research in the field of energy research, based on the previous basic research.

1 Introduction

Human space exploration has entered a new stage of development [1], and the requirement that equipment and consumables be launched from Earth into space limits the rate of space exploration. Increasing demand for space exploration necessitates additional resources to support the exploration process. Transporting equipment and consumables severely hinders the advancement of space exploration. The fundamental solution to this issue is to revolutionize the conventional method of launching equipment and consumables into space from Earth. In situ resource utilization (ISRU) is utilizing resources in space to produce products required for human activities in space exploration [2].

ISRU technology has become an essential tool for supporting the development of future space missions due to the growth of deep space exploration. ISRU technology primarily entails extracting, transforming, storing, and utilizing material resources under specific (extraterrestrial) environmental conditions. The United States National Aeronautics and Space Administration (NASA) identifies it as the first technology to be developed with priority for manned deep space exploration. This technology is integral to the entire process of space activities. It is also listed as one of the six technology fields the Chinese manned deep space exploration team will prioritize developing, believing it may have disruptive and transformative effects. Numerous bio-regenerative life support systems for space and solar system destinations, such as the moon and Mars, have been proposed for the ISRU [3]. Using microorganisms and higher organisms, methods from all areas of life range from the production and recovery of resources (such as oxygen, food, and material production, biomineralization, and wastewater recovery) to the provision of shelter and protection through energy generation and even terrain formation [4–8].

2 Development of chemical ISRU on Mars

Mars has been a primary focus of human space exploration for a long time [9]. Diverse directional systems have been proposed to use ISRU in space and throughout the solar system [10] to extend the duration of space exploration and establish space stations and celestial bases. Mars has become the center of attention in space due to its various possibly sustainable living conditions. The distance between Mars and Earth suits processing and supplying space missions. The average equatorial temperature on Mars is -14 °C, and in the absence of wind chill, the average body temperature is close to 1 °C, comparable to Earth's winter temperature. Mars has been discovered to have surface water and underground reservoirs. It has an atmosphere and is the primary source of CO2 and O2 from producing oxygen-based products for driving and inhaling air to create fuel. Plastics and other organic compounds can be manufactured under more advanced conditions. The climate is also essential as an operating environment for ISRU and other mission systems. In addition, the Martian weathering layer contains the remaining life-sustaining
elements. The Martian rotation cycle likely maintains basic human and plant circadian rhythms in the sun (equatorial annual solar irradiance of ~120 W/m², roughly equivalent to a Nordic-Martian day lasting 24 hours and 37 minutes). Mars is expected to become a new planet for humans to explore and potentially settle on in the near future due to the continuous advancement of various disciplines.

In 1978, Ash et al. conducted the first exhaustive feasibility study of the Mars ISRU, focusing on rocket propellant production for the Mars launch vehicle using carbon dioxide and water in the atmosphere to produce oxygen and ethane as oxidants and fuel mixture. In the subsequent years, numerous ISRU concepts were proposed, and NASA emphasized their significance in its design reference mission 5.0 [2]. DRA 5.0's primary proposed strategy for chemically achieving ISRU on Mars by producing CH₄ and O₂ is based on three chemical processes. Mars' O₂ production relies on the utilization of CO₂ and H₂O resources. Solid oxide CO₂ electrolysis (SOCE) can convert CO₂ to O₂, while water electrolysis can use water resources to produce H₂ and O₂. As to produce CH₄, the Sabatier reaction, which can convert H₂ and CO₂ to CH₄, is primarily responsible. Based on its technology, DRA 5.0 proposes three chemical ISRU strategies (Figure 1). The most likely initial strategy is the DRA 5.0 O₂-only strategy, which does not involve H₂ and only involves O₂; CH₄ is shipped from Earth, and O₂ is produced on Mars via SOCE. The other two strategies involve transporting H₂ from Earth (the H₂-only strategy) or producing H₂ on Mars through water electrolysis (the complete strategy) and converting H₂ to CH₄ via the Sabatier reaction. O₂ is produced for combustion via SOCE or H₂O electrolysis, respectively. However, the large volume of H₂ transport in this strategy, roughly three times that of the carrier spacecraft, and the need to supplement O₂ production through SOCE because the Sabatier reaction cannot produce enough O₂ to burn all the CH₄ produced are significant limitations for these two H₂-dependent chemical ISRU strategies.

3 Autotrophic microorganisms enable ISRU for biofuel production

The optimal way to harness biological in situ resources in space from the perspective of deploying energy production plants is to capture the energy and produce products within a single organism. As shown in figure 2.

4 Increased ISRU biofuel production capacity with heterotrophic strains

A biotechnology-enabled ISRU strategy for producing biofuels on Mars is proposed using the proposed short-chain diol compound as a Martian rocket propellant because it has higher heat values and sufficient Isp to launch human MAVs from the surface of Mars to low orbit on Mars. The bio-ISRU strategy includes the processes shown in Figure 3. First, cyanobacteria capture CO₂ from Mars and convert it into monosaccharides and essential nutrients as a starting point. Then, the biomass of cyanobacteria is digested by lysozyme, alpha-amylase, and glucoamylase, which engineered E. coli transforms into 2,3-butanediol (2,3-BDO) in a continuous process, simultaneously producing more than 20 tons of O₂ that could be utilized for Mars colonization. Biological and material optimizations resulted in a 32% reduction in power consumption, a 59% reduction in power consumption, and a 13% reduction in payload mass from Earth compared to the DRA 5.0 O₂-only strategy. It suggests that future in situ fuel production options for space exploration favor oxygenated compounds.
Combining autotrophic microorganisms with high fixed resource capacity and heterotrophic microorganisms with broad application and high yield can be a good choice for achieving ISRU in biofuel production.

As shown in Figure 3, Components of biofuel production are as follows: a) Cyanobacterial ponds (green): cultivation of cyanobacteria in photobioreactors or biofilm growth materials to utilize Martian resources and fix Martian atmospheric carbon. b) Cyanobacteria biomass digestion (yellow): cyanobacterial biomass treatment, membrane filtration concentration, and enzymatic degradation to produce engineered bacterial fermentation material. c) Microbial fermentation (blue): production of biofuel using cyanobacterial glucose. d) Biofuel extraction and separation (orange): enhancing the purity of biofuels via extraction and membrane separation. e) Biofuel applications on Mars (dark green): biofuels can be utilized in all fuel-required applications, including rocket propellants, transportation fuels, and mechanical power.

Low O2 levels in the Martian atmosphere impact the design of biofuels for use in space because the amount of O2 required for fuel combustion depends on the fuel's chemical composition. Oxygen-free compounds require more oxygen to aid combustion compared to oxygenated chemicals and must therefore transport more liquid oxygen (LOX) from Earth. For instance, 1 ton of CH4 combustion requires 4 tons of O2 whereas 1 ton of methanol (CH3OH) combustion requires only 1.5 tons of O2. Mars has a gravity of 3.73 m/s^2, which is only 38% of Earth’s. Even though oxygen atoms in oxygenated chemicals decrease the fuel’s heating value, the energy density requirements for fuel on Mars are low due to the planet’s lower gravity. Consequently, some of the chemicals can be used as space fuels. Table 1 displays the theoretical Isp values of several diols and higher alcohols, notably higher alcohols, to reduce oxygen consumption without compromising fuel performance.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Molecular formula</th>
<th>Combustion stoichiometry</th>
<th>HHV Isp (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>CH4</td>
<td>2 CH4 + 3 O2 —&gt; 2 H2O + CO2</td>
<td>55.7 459</td>
</tr>
<tr>
<td>Ethanol</td>
<td>C2H5OH</td>
<td>2 C2H5OH + 5 O2 —&gt; 6 H2O + 4 CO2</td>
<td>19.2 396</td>
</tr>
<tr>
<td>1,2-PDO</td>
<td>C3H4O2</td>
<td>C3H4O2 + 4 O2 —&gt; 3 H2O + CO2</td>
<td>24.0 412</td>
</tr>
</tbody>
</table>

Utilizing the accomplishments of metabolic engineering in biofuel production can expand the options for the bio-ISRU on Mars. The introduction of ethanol production pathways from Zymomonas mobilis into E. coli began pioneering work in biofuel metabolism engineering. The conversion of pyruvate to ethanol, which is facilitated by the heterologous expression of pyruvate decarboxylase and alcohol dehydrogenase in E. coli, results in the production of ethanol. Ethanol is the biofuel of the first generation, which has several disadvantages. As show in figure 4.

In addition to introducing high-yielding engineering strains to transform the di-gestible cyanobacteria biomass, indirect CO2 biotransformation technology can produce higher alcohols on Mars. The method divides the fixation of CO2 and the synthesis of products into two separate modules. First, CO2 is converted to C1 compounds such as formic acid via an efficient chemical immobilization method, and then the C1 compound is fed to engineering biofuels. Table 1 displays the theoretical Isp values of several diols and higher alcohols, notably higher alcohols (isobutanol, n-butanol, 2-methyl-1-butanol, 3-methyl-1-butanol), to reduce oxygen consumption without compromising fuel performance.
5 Conclusions

The use of ISRU to produce biofuel on Mars has vast potential, ensuring that the products are sustainable and environmentally friendly. ISRU for biofuel production has the potential to connect with life support systems to construct a network architecture for the entirety of the space exploration process and realize the entire process cycle. The ongoing development of synthetic biology and metabolic engineering technology is used to upgrade and transform production strains and use scenarios for space exploration, maximizing the application of biofuel production channels.

Although biofuels are widely regarded as a promising future technology, their use on Mars still presents several obstacles. Extremely harsh chemical conditions on the surface of Mars necessitate the use of specialized technologies and equipment to produce biofuel. Producing biofuel on Mars is prohibitively expensive due to the infrastructure and labor requirements. The bio-ISRU strategy allows production of biofuels at a lower cost. However, it is still constrained by rate-limiting steps, such as cyanobacteria biomass productivity and microbial fermentation capacity. Future research is anticipated to improve the ISRU strategy for biofuels considering the ongoing advancement of synthetic biology, genetic engineering, metabolic engineering, and the constant evolution of technology.

Future life support systems will also benefit from the production of biofuels on Mars’ surface. They are promising prospects for deploying various microbial factories in space. Integrate the bio-ISRU strategy and other life support systems, deploy micro-bial manufacturing plants in space, and combine different technical purposes to establish a system that facilitates the recycling of various types of energy, realize the establishment of a sustainable production system in space, and break the limitations of Earth resource transportation on future space exploration. Before the actual mission of the Mars bio-ISRU strategy can be implemented, a comprehensive test on Earth is required to simulate the impact of actual mission implementation on Mars, despite the low risk of microbial contamination under the influence of the Martian environment.

Since the industrial revolution, human demand for energy has increased abruptly, and the exploitation of energy sources such as oil and wood has continued to increase. Although these energy sources have made a significant contribution to the development of human society, the earth’s environment has been seriously polluted with them, and if this problem is not solved, human society will not only stop developing and suffer from environmental antipathy, but even pose a threat to our survival.

References