

EVALUATING MICROGRAVITY EFFECTS ON MICP PERFORMANCE FOR LUNAR IN-SITU RESOURCE UTILIZATION

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*Corresponding Author, Received: 16 May 2025, Revised: 29 Nov. 2025, Accepted: 05 Dec. 2025

ABSTRACT: The loose regolith on the lunar surface presents significant challenges for base construction. Microbially induced carbonate precipitation (MICP) has been proposed as a promising method for enhancing lunar regolith strength. However, the microgravity environment may affect microbial growth and mineralization efficiency, potentially influencing the feasibility of MICP-based stabilization. This study investigated the microbial growth behavior, urease activity, and microstructural changes of *Lederbergia lenta* (RII-2) under different culture medium and gravitational conditions. Experiments were conducted using NH₄-YE, R2A, and R2A-Urea medium to assess bacterial performance over 168 h. The results indicate that RII-2 exhibited the highest OD₆₀₀ value in R2A-Urea medium, significantly surpassing NH₄-YE and R2A. Urease activity tests revealed that R2A-Urea medium exhibited the highest overall enzymatic activity among the three media. Under microgravity conditions, RII-2 showed a 40% increase in OD₆₀₀ and a 22-28% decline in urease activity compared to normal gravity. These findings suggest that experimental conditions affect bacterial growth and enzymatic function, which may impact the efficiency of regolith stabilization by MICP in space environments.

Keywords: Lunar regolith stabilization, Microbially induced carbonate precipitation (MICP), Microgravity, Bacteria growth, Urease activity

1. INTRODUCTION

The establishment of permanent infrastructure on the Moon is a key objective in advancing extraterrestrial exploration. However, this goal is significantly constrained by the need to transport large quantities of construction materials from Earth, which imposes severe logistical and economic burdens. As a result, attention has shifted toward utilizing in-situ resources, particularly the abundant lunar regolith, as a primary construction material. The lunar surface is covered by a layer of regolith formed through continuous meteoritic bombardment and long-term space weathering [1–3]. This layer is characterized by its fine-grained, angular texture, low density, and lack of cohesion [4], resulting in poor bearing capacity, high surface permeability, and susceptibility to dust dispersion and particle detachment [5]. These issues not only hinder direct construction activities but also lead to high risks for rovers, landers, and machinery operation due to severe abrasion, dust contamination, and surface instability. In addition, the weak interparticle bonding limits the formation of load-bearing structures, making it difficult to support foundations or resist external stress from lunar thermal fluctuations and meteorite impacts. Therefore, effective solidification and mechanical reinforcement of the regolith are essential prerequisites for enabling stable, durable, and sustainable lunar surface operations.

Among various ground improvement strategies, Microbially Induced Carbonate Precipitation (MICP)

has attracted increasing attention as a biologically mediated method for stabilizing loose granular soils [6, 7]. MICP utilizes the urease activity of specific microorganisms to catalyze urea hydrolysis, leading to the formation of carbonate ions that react with calcium to precipitate calcium carbonate (CaCO₃), which serves as a bonding agent between particles [8]. Through this mechanism, soil grains can be partially cemented, improving strength, stiffness, and erosion resistance while maintaining relatively low energy requirements.

In contrast to conventional solidification methods that typically rely on thermal treatment, chemical admixtures, or high-pressure compaction—processes that often require heavy equipment and externally supplied materials [9], MICP operates under mild conditions using biologically derived reactions [10]. This makes it highly suitable for in-situ ground stabilization in remote or resource-limited environments, particularly when the use of external binders or heavy machinery is impractical. Moreover, MICP processes can be adjusted by controlling parameters such as nutrient concentration, bacterial density, calcium source, or reaction time, providing flexibility for different engineering needs.

However, the effectiveness of MICP is strongly governed by microbial activity, enzyme expression, and chemical transport processes [11]. As a biologically driven method, its performance is therefore sensitive to external physical conditions, including temperature, pH, ionic strength, and particularly gravitational forces. Since both bacterial

proliferation and urease-mediated reactions are closely linked to fluid dynamics and mass transfer, variations in gravity may alter sedimentation behavior, nutrient availability, and biomineralization kinetics. Consequently, understanding how gravity influences biological and mineralization processes is essential before MICP can be applied in extraterrestrial environments such as the Moon or Mars. Considering these considerations, the present study explores the potential of MICP under simulated microgravity conditions, focusing on microbial growth behavior and urease activity. By comparing these processes with those observed under normal gravity, the work aims to clarify how microgravity may influence the biological behavior involved in MICP, thereby providing a basis for future application in space-related environments.

2. RESEARCH SIGNIFICANCE

This study provides fundamental insights into the feasibility of applying MICP in space-related environments. By systematically examining bacterial growth and urease activity under different nutrient and gravitational conditions, the work clarifies the biological limitations and adaptability of ureolytic bacteria in microgravity. The findings contribute to understanding how environmental constraints affect biomineralization efficiency, offering essential scientific evidence for future extraterrestrial ground stabilization. These results can support the development of bio-based construction strategies and promote the practical implementation of in-situ resource utilization (ISRU) on the lunar surface.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Bacteria

The ureolytic bacterium *Lederbergia lenta* (RII-2), isolated in previous studies at Hokkaido University, was used in this study. This strain was selected because it has been previously confirmed to exhibit stable urease activity and reproducible growth performance in MICP-related experiments, making it suitable as a reference strain for assessing environmental effects. Glycerol stocks were prepared and stored at $-80\text{ }^{\circ}\text{C}$ to preserve bacterial viability, and pre-cultures were initiated in $\text{NH}_4\text{-YE}$ liquid medium before each experiment. This ensured consistent physiological conditions for all trials and allowed the subsequent effects of medium composition and gravity to be evaluated under controlled and reliable initial conditions.

3.1.2 Culture medium

To accurately evaluate bacterial growth and urease activity under varying conditions, it was first

necessary to identify an appropriate culture medium. Since medium composition strongly affects bacterial proliferation and enzyme expression, a comparative approach was adopted to distinguish the effects of nutrient richness from those of urea availability. Therefore, three media were selected to systematically examine the influence of nutrient availability and urea supplementation on RII-2. The detailed compositions of the three media are listed in Table 1.

(1) $\text{NH}_4\text{-YE}$ Medium: A nutrient-rich medium used extensively in previous MICP research, known to support rapid cell growth and high biomass. Its well-documented performance provides a reliable reference for evaluating microbial activity under favorable growth conditions, and thus it served as a benchmark for optimal conditions [13].

(2) R2A Medium: A minimal medium typically used for environmental isolations, chosen to simulate low-nutrient environments similar to those encountered in extraterrestrial settings where resource input must be limited [14]. Using this medium allows the assessment of bacterial adaptability under resource constraints, which is critical for evaluating the feasibility of MICP in space-related applications.

(3) R2A-Urea Medium: A variation of R2A containing urea as a direct substrate for urease activity. This medium bridges the gap between nutrient limitation and enzymatic activation, enabling investigation of whether urease synthesis can be triggered solely by the availability of urea, without relying on ammonium-based nitrogen. It also provides a controlled condition for examining the induction of biomineralization-related pathways under minimal nutrient supply.

Table 1. Composition of three types of culture medium (per 100 mL, solvent: distilled water)

Medium	Component	Amount (g)
$\text{NH}_4\text{-YE}$	Yeast Extract	4.00
	Ammonium Sulfate	2.00
	Tris aminomethane	1.58
R2A	R2A Medium	0.32
R2A-Urea	R2A Medium	0.32
	Urea	0.60

3.2 Methods

3.2.1 Bacteria cultivation

Pre-cultures of RII-2 were prepared by inoculating 1 mL of glycerol stock into 5 mL of sterilized $\text{NH}_4\text{-YE}$ medium in test tubes, followed by incubation at $30\text{ }^{\circ}\text{C}$ with shaking at 160 rpm for 24 h.

This step was performed to activate the bacterial metabolism and ensure a uniform physiological state prior to experimental use, thereby minimizing variability among trials.

For the main cultivation, 0.4 mL of the pre-cultured suspension was transferred to 25 mL vented-cap flasks (Falcon® 353018) containing 42 mL of one of the three test media (NH₄-YE, R2A, or R2A-Urea). Care was taken to prevent air bubbles during filling to avoid the introduction of excess oxygen, which could influence both bacterial proliferation and urease expression. For each condition, six replicate flasks were prepared to ensure statistical reliability and facilitate comparison across different media and gravitational environments.

3.2.2 Microgravity and normal gravity experimental setup

To evaluate the effect of gravitational conditions on bacterial behavior, cultures were incubated under both simulated microgravity and standard gravity. Simulated microgravity was generated using a rotating wall vessel bioreactor (Zeromo CL-1000, Yamato Scientific Co., Ltd.), where the culture flasks were mounted horizontally and rotated continuously during incubation. This configuration minimizes gravitational settling and creates a suspended cultivation state, allowing the bacteria to remain evenly distributed in the medium throughout the incubation period. By maintaining a constant rotational speed that prevents sedimentation, the direction of the gravitational vector is randomized over time. As a result, mass transfer becomes diffusion-dominated, reproducing a low-shear environment that closely resembles microgravity conditions encountered in space laboratories. This dynamic state suppresses convective flow and mimics a microgravity environment suitable for biological studies.

In contrast, control cultures were placed statically in an incubator under normal gravity. Keeping the two systems physically isolated helped eliminate cross-influence during incubation and ensured that gravity remained the sole variable. Both setups were maintained at 30 °C, and humidity was kept high by placing water-saturated towels inside the incubators to minimize evaporation. As shown in Fig. 1, sampling was performed at 48, 120, and 168 h for OD₆₀₀ and urease activity measurements.

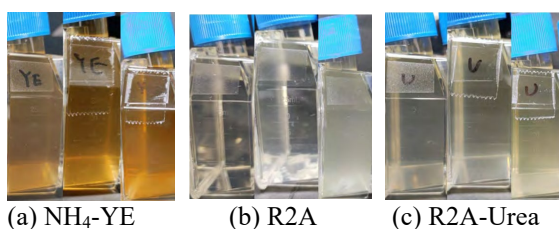


Fig.1 After 48,120,168 h of culture medium

3.2.3 Optical density (OD₆₀₀) measurement

To evaluate the growth behavior of RII-2 under different nutrient and gravitational conditions, OD₆₀₀ was measured as an indicator of bacteria concentration over time [15]. Sampling was performed at 48, 120, and 168 h after the start of cultivation. Prior to measurement, each flask was gently agitated to ensure a homogeneous suspension. A portion of the culture liquid was then transferred to a disposable cuvette, and OD₆₀₀ was measured using a UV-visible spectrophotometer (V-730, JASCO Corporation). Measurements were conducted in triplicate for each condition to ensure reproducibility.

3.2.4 Urease activity test

To evaluate the enzymatic activity of RII-2 under varying medium and gravity conditions, urease activity was measured using two methods: the indophenol colorimetric method and the electrical conductivity (EC) method. Using both techniques allowed cross-validation of results and minimized the potential influence of medium composition on a single measurement approach.

The indophenol colorimetric method was employed to quantify urease activity by indirectly measuring the concentration of NH₄⁺ produced during urea hydrolysis. In this method, NH₄⁺ released from the enzymatic breakdown of urea react with phenol nitroprusside and sodium hypochlorite to form a blue-colored compound, indophenol, whose absorbance at 630 nm is proportional to the amount of ammonium generated. Since the production of NH₄⁺ is stoichiometrically linked to urease activity, the rate of absorbance increase over time provides a quantitative indicator of enzymatic performance.

The EC method estimates urease activity by measuring the increase in ionic concentration resulting from urea hydrolysis. As urease catalyzes the breakdown of urea, ions such as NH₄⁺ and HCO₃⁻ are released, increasing the electrical conductivity. For each measurement, 0.5 mL of culture was added to 50 mL of urea solution pre-equilibrated at 30°C. Conductivity was measured every 5 min for 20 min using a portable conductivity meter (LAQUAtwin EC-33, HORIBA).

4. RESULTS AND DISCUSSIONS

To evaluate the biological feasibility of applying MICP under space-relevant conditions, the performance of RII-2 was assessed across varying culture medium and gravitational environments. The analysis focused on two key biological indicators, that is bacterial growth and urease activity, which directly govern microbial proliferation and the rate of carbonate formation in MICP. By comparing their responses under normal gravity and simulated microgravity, the adaptability of RII-2 to reduced-gravity environments was examined, allowing the

identification of potential limitations and favorable conditions for MICP implementation. The results provide a basis for determining whether microbial-driven carbonate precipitation can be maintained in low-shear environments and for establishing suitable cultivation strategies when applying MICP beyond terrestrial settings.

4.1 OD₆₀₀

Fig. 2 presents the growth curves of RII-2 cultivated in three different media: NH₄-YE, R2A, and R2A-Urea. At 48 and 120 h, the NH₄-YE medium exhibited the highest OD₆₀₀ values, indicating superior cell proliferation under nutrient-rich conditions. The consistent growth observed in NH₄-YE is attributed to the availability of both organic nitrogen and inorganic nitrogen, which together support rapid microbial metabolism and reduce the lag phase that typically occurs during early cultivation. In addition, the higher metabolic activity enabled faster utilization of carbon sources and the maintenance of active replication, resulting in continuous biomass accumulation throughout the incubation period. This trend confirms that NH₄-YE can be regarded as the optimal nutrient environment for RII-2 and serves as a reference condition for evaluating growth responses under limited-nutrient and microgravity conditions.

In contrast, the R2A medium displayed negligible growth during the initial 120 h, followed by a sharp increase in OD₆₀₀ to approximately 0.45 at 168 h. This pattern suggests an extended lag phase in low-nutrient conditions, potentially due to slower metabolic activation or delayed adaptation. The delayed proliferation indicates that RII-2 required additional time to synthesize essential enzymes and adjust its metabolism to sustain growth under limited substrate availability. Once adaptation occurred, the bacteria appeared to utilize the available nutrients more efficiently, leading to a rapid increase in biomass during the later stage of cultivation.

The R2A-Urea medium showed moderate and steady growth throughout the cultivation period, with OD₆₀₀ values increasing gradually from 0.23 to 0.26, indicating that the addition of urea partially improved nitrogen availability but did not fully compensate for the nutrient limitations inherent in the base R2A formulation. This suggests that urea alone was insufficient to support rapid proliferation but was adequate to sustain basic metabolic activity, resulting in slow yet consistent biomass accumulation. The steady growth trend also implies that R2A-Urea can provide a stable culture environment, which is beneficial for examining enzyme expression and urease induction under controlled conditions and was therefore selected as the medium for subsequent microgravity experiments.

These results demonstrate that NH₄-YE is the

most effective medium for promoting early-stage bacterial growth, while R2A supports delayed but significant proliferation. R2A-Urea provides an intermediate growth environment, with modest improvement over R2A alone. The differences in OD₆₀₀ trends underscore the importance of medium composition in regulating bacterial growth dynamics.

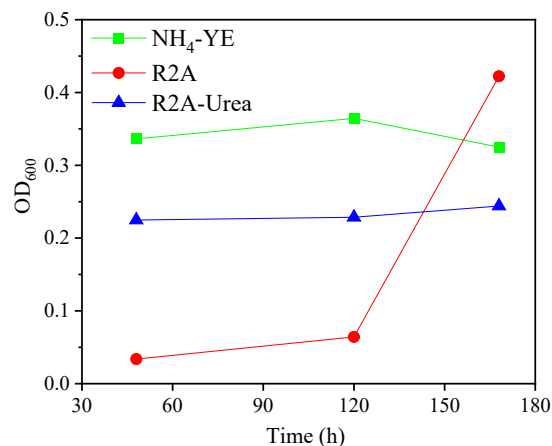


Fig. 2 OD₆₀₀ with different culture medium

4.2 Urease Activity

Urease activity of RII-2 was examined in three different media using both the indophenol colorimetric method and EC method. As shown in Fig. 3 to 5, the NH₄-YE medium supported vigorous cell growth but yielded lower urease activity values, with negative values observed particularly at 48 h. This phenomenon may be attributed to the chemical complexity of the medium, which can introduce background signals or interfere with ion-sensitive measurements, especially under conditions where enzymatic activity remains low relative to baseline conductivity or optical density. Additionally, the high nutrient concentration may promote biomass accumulation without strongly inducing urease expression, leading to a dilution effect where enzyme production per cell decreases. As a result, the total enzyme activity in NH₄-YE may appear suppressed despite active bacterial proliferation, suggesting that this medium is less suitable for evaluating urease-driven MICP processes compared with nutrient-limited formulations.

In the R2A medium, moderate urease activity was observed, with values generally decreasing over time. This decline may reflect a gradual loss of enzyme functionality under nutrient-limited conditions. Additionally, a wider discrepancy between the two measurement methods was observed, likely due to the limited buffering and ionic capacity of the base medium, which amplifies variability in both optical and conductivity-based assays.

In contrast, the R2A-Urea medium demonstrated stable and reproducible urease activity profiles across

all time points, with consistent agreement between the two analytical methods. The inclusion of urea provided a direct and sustained substrate source, while the simpler background composition minimized interference with both optical and electrochemical measurements.

In terms of total urease activity, R2A-Urea medium exhibited the highest values among the three tested media, indicating strong overall enzyme production. However, when normalized by OD₆₀₀ to reflect catalytic efficiency per unit biomass, R2A showed the highest specific activity, reaching approximately 3.22 U/mL, compared to 1.29 U/mL in R2A-Urea and 0.31 U/mL in NH₄-YE. Despite not having the highest unit activity, R2A-Urea was ultimately selected for microgravity experiments due to its stable and reproducible measurements, low bacterial aggregation, and good consistency between the EC and indophenol methods. These characteristics made it the most practical and reliable medium for evaluating MICP performance under space-relevant conditions.

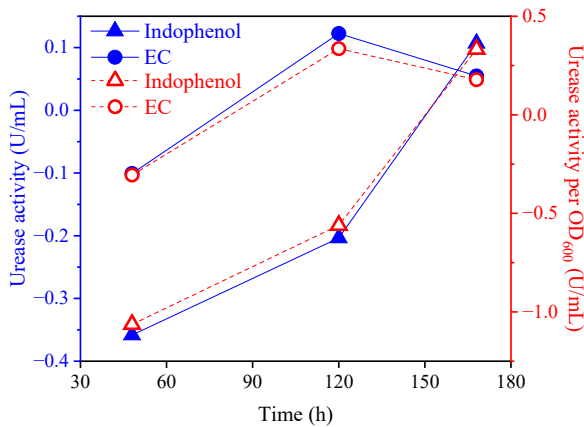


Fig. 3 Urease activity of RII-2 in NH₄-YE medium

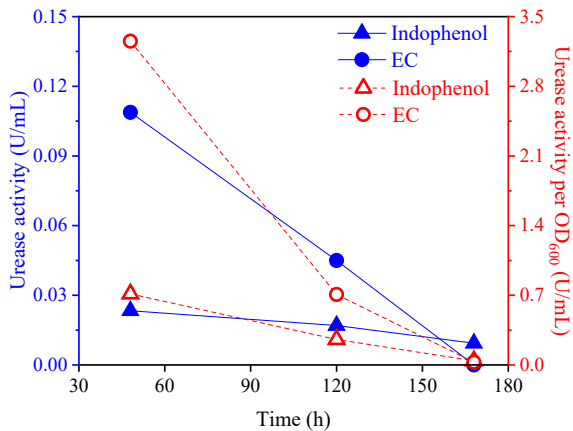


Fig. 4 Urease activity of RII-2 in R2A medium

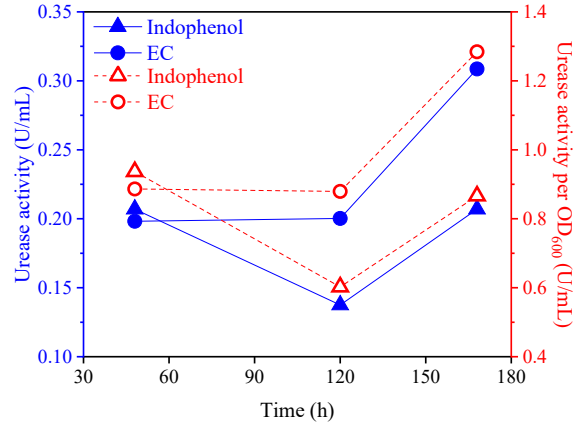


Fig. 5 Urease activity of RII-2 in R2A-Urea medium

4.3 Microgravity and Normal Gravity

To evaluate the effects of gravitational conditions on microbial growth, RII-2 was cultivated in R2A-Urea medium under simulated microgravity and normal gravity. R2A-Urea was selected based on prior evaluation of growth stability and minimal aggregation, making it suitable for use in rotating wall vessel systems. As shown in Fig. 6, cultures under simulated microgravity consistently exhibited higher OD₆₀₀ values than those incubated under normal gravity. After the initial 24 h, OD₆₀₀ values in the microgravity condition stabilized within the range of 0.33 to 0.41, whereas those under normal gravity remained between 0.22 and 0.30. The maximum difference between the two conditions reached approximately 0.12, corresponding to a relative increase of nearly 40% in bacterial suspension density under microgravity.

In the microgravity system, continuous horizontal rotation of the culture vessel disperses the gravitational vector over time, thereby reducing sedimentation and suppressing shear forces. This creates a low-shear, diffusion-dominated environment in which bacteria remain suspended and experience more uniform access to nutrients. Such conditions help delay cell settling and reduce localized gradients, which are commonly observed in static cultures under normal gravity. The microgravity environment may also contribute to more stable local environments around bacteria, supporting sustained metabolic activity and biomass accumulation. This could explain the higher OD₆₀₀ values observed under microgravity, suggesting that the reduced gravitational influence does not inhibit proliferation and may even facilitate continuous cell suspension and prolonged growth.

These findings suggest that RII-2 can maintain active proliferation under microgravity, with growth levels exceeding those observed under normal gravity despite the low-nutrient conditions provided by the R2A-Urea medium. This implies that reduced

gravitational forces do not impair, and may even enhance, the growth of ureolytic bacteria under appropriately controlled conditions. The absence of sedimentation likely improved nutrient accessibility across the culture vessel, allowing cells to remain in suspension for longer periods and sustain metabolic activity. Therefore, microgravity did not hinder bacterial growth and may create a more favorable environment for maintaining a dispersed cell population, which is beneficial for uniform biomineralization in MICP applications.

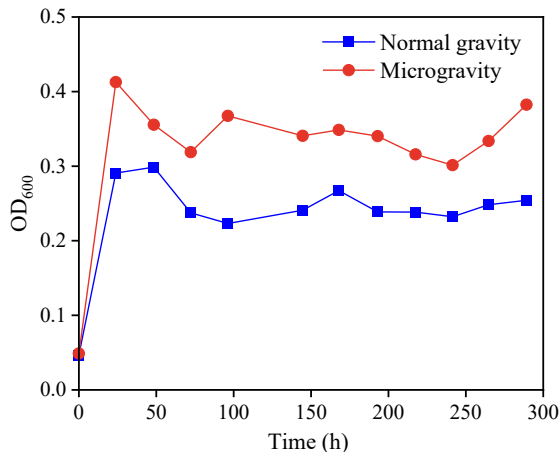


Fig. 6 OD₆₀₀ under different gravity environment

Fig. 7 illustrates the variation in urease activity under microgravity and normal gravity conditions. While both conditions supported sustained enzymatic activity, urease efficiency was consistently lower under microgravity at most time points. The difference was particularly evident after 96 h, where activity values under microgravity generally ranged between 0.5 and 0.7 U/mL, while those under normal gravity were maintained at 0.7 to 0.9 U/mL. On average, urease activity under microgravity was 22–28% lower across the cultivation period. This reduction suggests that although cell proliferation was enhanced in the microgravity environment, the induction or regulation of urease enzymes may have been suppressed, resulting in a lower catalytic efficiency per unit biomass. Such behavior indicates that enzyme expression is more sensitive to gravitational change than growth, which may affect the overall rate of carbonate precipitation in MICP processes under reduced gravity.

This trend may reflect disruptions in the regulatory processes governing urease expression in bacteria. As an inducible enzyme, urease production involves multi-level control, including transcriptional activation, cofactor incorporation, and protein maturation. Microgravity may interfere with intracellular organization or spatial gene regulation, impairing the coordinated responses required for efficient enzyme expression. Furthermore,

gravitational changes can affect ribosomal function and protein folding kinetics in bacteria, potentially reducing the yield or catalytic integrity of urease even in growing populations. These effects indicate that enzyme-related metabolic pathways are more sensitive to gravitational variation than general cell proliferation, highlighting urease activity as a critical limiting factor for MICP under reduced gravity. Understanding these biological constraints is therefore essential for predicting carbonate precipitation efficiency and optimizing MICP strategies for space applications.

These results suggest that the reduction in urease activity per OD₆₀₀ under microgravity may compromise the overall efficiency of MICP. Even if sufficient bacteria are present, a slower rate of urea hydrolysis could lead to delayed or insufficient CaCO₃ precipitation, especially in time-sensitive or structurally demanding applications. In addition, lower enzymatic output may affect the spatial uniformity of precipitation, potentially resulting in uneven solidification. This limitation should be considered when evaluating the feasibility of MICP-based soil stabilization in extraterrestrial environments, where consistent strength development and process controllability are essential.

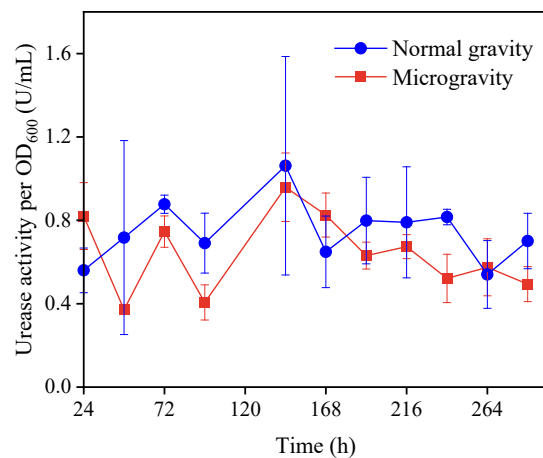


Fig. 7 Urease activity under different gravity environment

5. CONCLUSIONS

This study systematically evaluated the growth behavior and urease activity of the ureolytic bacterium RII-2 under varying culture media and gravitational conditions, with the aim of assessing the feasibility of MICP in space environments. The conclusions are summarized as follows:

(1) R2A-Urea supported the most robust microbial growth and the highest total urease activity among the three tested media. While NH₄-YE facilitated moderate bacterial proliferation, it showed low and unstable enzymatic output. R2A, despite

exhibiting higher specific activity per biomass, was limited by poor growth, resulting in lower overall enzyme production. These characteristics established R2A-Urea as the most suitable medium for subsequent microgravity experiments.

(2) Bacterial growth, as measured by OD₆₀₀, was not impaired under simulated microgravity. In fact, proliferation was enhanced compared to static controls, likely due to reduced sedimentation and improved suspension homogeneity.

(3) Despite increased biomass, urease activity per OD₆₀₀ was moderately reduced under microgravity. This indicates that gravitational changes may influence enzyme regulation or cofactor dynamics, which could limit the overall carbonate precipitation rate in MICP processes.

6. REFERENCES

1. Dong Z., Fang G., Zhou B., et al. Properties of Lunar Regolith on the Moon's Farside Unveiled by Chang'E - 4 Lunar Penetrating Radar[J]. *Journal of Geophysical Research: Planets*, 2021, 126(6): e2020JE006564.
<https://doi.org/10.1029/2020JE006564>
2. Chen Y., Tian A., Min G., Fukuda D., and Kawasaki S. An overview on lunar regolith simulants solidification methods: integrating chemical, physical, and MICP strategies for extraterrestrial construction. [J]. *Biogeotechnics*, 2025, 100212.
<https://doi.org/10.1016/j.bgtech.2025.100212>
3. Vanga S., Fassett C I., Zanetti M., et al. Rock abundance on the lunar mare on surfaces of different age: Implications for regolith evolution and thickness[J]. *Geophysical Research Letters*, 2022, 49(4): e2021GL096710.
<https://doi.org/10.1029/2021GL096710>
4. Osinski G R., Melosh H J., Andrews-Hanna J., et al. Lunar impact features and processes[J]. *Reviews in Mineralogy and Geochemistry*, 2023, 89(1): 339-371.
<https://doi.org/10.2138/rmg.2023.89.08>
5. Subramanian S., Wilson A., White C., et al. Crater formation and particle ejection induced by supersonic jet impingement in near-vacuum[J]. *Acta Astronautica*, 2025, 232: 439-452.
<https://doi.org/10.1016/j.actaastro.2025.03.017>
6. Jiang L., Xia H., Wang W., et al. Applications of microbially induced calcium carbonate precipitation in civil engineering practice: A state-of-the-art review[J]. *Construction and Building Materials*, 2023, 404: 133227.
<https://doi.org/10.1016/j.conbuildmat.2023.133227>
7. Tian A., Tang X., Chen J., and Hu M. AC-assisted microbially induced carbonate precipitation for sand reinforcement: An experimental study[J]. *Geomechanics for Energy and the Environment*, 2024. 40, 100609.
<https://doi.org/10.1016/j.gete.2024.100609>
8. Jiang L., Xia H., Wang W., et al. Applications of microbially induced calcium carbonate precipitation in civil engineering practice: A state-of-the-art review[J]. *Construction and Building Materials*, 2023, 404: 133227.
<https://doi.org/10.1016/j.conbuildmat.2023.133227>
9. Xu F., Wang D.. Review on soil solidification and heavy metal stabilization by microbial-induced carbonate precipitation (MICP) technology[J]. *Geomicrobiology Journal*, 2023, 40(6): 503-518.
<https://doi.org/10.1080/01490451.2023.2208113>
10. Fouladi A S., Arulrajah A., Chu J., et al. Application of Microbially Induced Calcite Precipitation (MICP) technology in construction materials: A comprehensive review of waste stream contributions[J]. *Construction and Building Materials*, 2023, 388: 131546.
<https://doi.org/10.1016/j.conbuildmat.2023.131546>
11. Ludtka C., Silberman J., Moore E., et al. Macrophages in microgravity: the impact of space on immune cells[J]. *npj Microgravity*, 2021, 7(1): 13.
<https://doi.org/10.1038/s41526-021-00141-z>
12. Salavatifar M., Ahmadi S M., Todorov S D., et al. Impact of Microgravity on Virulence, Antibiotic Resistance and Gene Expression in Beneficial and Pathogenic Microorganisms[J]. *Mini Reviews in Medicinal Chemistry*, 2023, 23(16): 1608-1622.
<https://doi.org/10.2174/1389557523666230109160620>
13. Liu S., Ding X., Song P., et al. Effects of nitrogen sources on MICP-related metabolic mechanism of *Sporosarcina pasteurii* and soil reinforcement[J]. *Journal of Rock Mechanics and Geotechnical Engineering*, 2024, 16(12): 5147-5161.
<https://doi.org/10.1016/j.jrmge.2024.11.001>
14. Fagervold S K., Rohée C., and Lebaron P. Microbial consortia degrade several widely used organic UV filters, but a number of hydrophobic filters remain recalcitrant to biodegradation[J]. *Environmental Science and Pollution Research*, 2023, 30(60): 125931-125946.
<https://doi.org/10.1007/s11356-023-31063-w>
15. Huang H., Jia M., Peng D., et al. Polyethylene microplastics interfere with MICP-based cadmium remediation: A dual-system evaluation of microbial performance and environmental response[J]. *Journal of Hazardous Materials*, 2025, 139541.
<https://doi.org/10.1016/j.jhazmat.2025.139541>