



ЕКОЛОГІЯ

UDC 574.5+523.3

DOI <https://doi.org/10.32782/naturaljournal.15.2026.22>

DYNAMICS OF GERMINATION OF BULBS OF CULTIVATED REPRESENTATIVES OF THE GENUS ALLIUM L.

I. V. Khomiak¹

*This publication investigates the fundamental prospects and physiological parameters of cultivating domesticated representatives of the genus *Allium* utilizing lunar regolith simulants derived from the basaltic compositions of lunar maria surfaces. The primary focus of this empirical study is centered on the application of the ETL-1 lunar regolith simulant, a high-fidelity substrate engineered to replicate the mineralogical and physical properties of the Moon's lunar seas. The experimental subjects selected for this astrobotanical research include a specific garlic cultivar, «Gulyaipilsky» (*Allium sativum*), and a specialized onion cultivar, «Strihunivska» (*Allium cepa*). To establish a rigorous scientific baseline for the comparative analysis, a control group was maintained using pure, triple-washed quartz sand, which provided a chemically inert medium for plant development. Throughout the duration of the cultivation period, the irrigation protocol was strictly limited to distilled water, intentionally omitting any external mineral supplementation or hydroponic nutrient additives. This methodological constraint was implemented to isolate the intrinsic capacity of the ETL-1 regolith to function as a potential growth medium and to assess its spontaneous chemical contribution to the plant's metabolic requirements. The overarching objective of the present work is to explore the feasibility of utilizing lunar maria regolith as a primary hydroponic or solid-substrate medium within the closed-loop agroecosystems of future stationary lunar outposts. In pursuit of this goal, several critical tasks were addressed: to examine the fundamental potential of the ETL-1 simulation for supporting the growth of cultivars within the genus *Allium*; to model the dynamics of biomass accumulation and the potential for carbon dioxide sequestration on this specific substrate in the absence of exogenous nutrient inputs; to determine the overall capacity for agricultural production using lunar basaltic material as a functional hydroponic component. The empirical findings indicate that the ETL-1 lunar maria regolith simulant does not exert any acute aggressive or inhibitory phytotoxic influence on the seedlings. Germination phenology recorded the emergence of the first sprouts on the 16th day for the «Gulyaipilsky» garlic and on the 11th day for the «Strihunivska» onion. The vegetative growth of *Allium cepa* shoots continued for a total of 43 days, while the growth phase for *Allium sativum* shoots persisted for 45 days. By the termination of the experiment, the average shoot height for onions cultivated on the regolith simulant reached 27.3 cm, whereas the garlic shoots attained an average height of 10.21 cm. These systematic observations allow for the formulation of a significant scientific hypothesis: the presence of specific mineral nutrients inherent to the lunar regolith results in their gradual dissolution into the aqueous soil solution. This process likely facilitates a partial compensation for the endogenous chemical depletion of the bulb's internal resources expended during the intensive stages of vertical growth, suggesting that lunar regolith may provide a more supportive mineral environment than inert sand for future extraterrestrial agriculture.*

Key words: substrate hydroponics, extraterrestrial agroecosystems, lunar colonization, astroecology.

¹ Doctor of Biological Sciences, Associate Professor, Professor at the Department of Ecology and Geography (Zhytomyr Ivan Franko State University, Zhytomyr) e-mail: ecosystem_lab@ukr.net ORCID: 0000-0003-0080-0019

ДИНАМІКА ПРОРОСТАННЯ ЦИБУЛИН КУЛЬТУРНИХ ПРЕДСТАВНИКІВ РОДУ ALLIUM L.

І. В. Хом'як

У публікації розглядаються можливості вирощування культурних представників роду Allium на місячному реголіті із поверхні місячних морів. У дослідженні було використано симуляцію місячного реголіту ETL-1, часник сорту «Гуляйпільський» та цибуля сорту «Стригунівська». Для контрольного експерименту було використано чистий промитий кварцовий пісок. Вирощування супроводжувалося поливом дистильованою водою без додавання елементів мінерального живлення. Метою роботи є вивчення можливості використання місячного реголіту із поверхні місячних морів, як гідропонічного субстрату агрокосистем стаціонарних баз на Місяці. В рамках мети було необхідно: дослідити потенціал використання імітації місячного реголіту ETL-1 для вирощування культурних сортів роду Allium, змодельовати потенціал поглинання вуглекислого газу та нарощування біомаси на симуляції місячного реголіту ETL-1 без додавання поживних речовин; визначити потенціал вирощування культурних рослин роду Allium на гідропонічному субстраті у вигляді місячного реголіту із поверхні місячних морів. Симулятор місячного реголіту місячних морів ETL-1 не проявляє агресивної або пригнічуючої дії на саджанці. Перші паростки з'являються на 16 день для часнику сорту «Gulyaipilsky» та цибулі на 11 день для цибулі сорту «Strihunivska». Ріст пагонів Allium сера продовжується 43 дні з моменту і 45 днів пагонів Allium sativi. Середня висота пагонів на кінець експерименту для цибулі на симуляторі реголіту дорівнює 27,3 см і 10,21 для часнику. Спостереження дозволяють висунути гіпотезу про те, що наявність деяких елементів мінерального живлення в реголіті призводить до їхнього потрапляння в водний розчин, що частково компенсує втрати хімічних речовин цибулини, витрачених на ріст.

Ключові слова: субстратна гідропоніка, позаземні агрокосистеми, колонізація Місяця, астроекологія.

Introduction

In the 21st century, we are witnessing a distinct resurgence of the «Lunar Race» (Moon Race 2.0); however, the contemporary landscape is defined by driving forces and participants that differ significantly from those characterizing the Cold War era between the United States and the Soviet Union (Ferl & Paul, 2010). Today, a multifaceted complex of geopolitical, economic, scientific, and technological factors serves as the catalyst for this renewed competition. Currently, the primary antagonists in this race are the People's Republic of China (PRC) and the United States, mirroring historical dynamics wherein the U.S. felt compelled to respond to the ambitions and milestones of the Soviet space program. To some extent, this process resembles a repetitive cycle: initially, the PRC aimed to replicate the fundamental lunar achievements realized by the U.S. in the 20th century, notably through the successful landings executed under the «Chang'e Project», which commenced in 2004. This strategic progression necessitated a formal response from the United States, leading to the inauguration of NASA's "Artemis" program in 2017. The success of such national initiatives serves as a critical demonstration of technological sovereignty and superiority, fostering a

prestigious international image that bolsters a nation's political standing and investment attractiveness. Furthermore, achieving a dominant presence provides a strategic advantage in the establishment of regulatory frameworks and norms for the exploitation of outer space. Legally, the equality of nations remains largely nominal, both on Earth and in the context of lunar exploration; consequently, those entities maintaining the strongest positions in space will exert disproportionate influence over the rules governing its utilization and governance.

Another significant driver for the resurgence of the lunar race is rooted in economic strategic interests and the potential exploitation of natural resources. The Moon is increasingly regarded as a highly promising extraterrestrial hub for well-established industrial sectors, ranging from advanced telecommunications and spacecraft maintenance to specialized pharmacology and high-precision electronics manufacturing. Furthermore, substantial emphasis must be placed on Helium-3, which is widely considered the most viable energy resource for the foreseeable future due to its potential as a fuel for clean nuclear fusion. Therefore, the establishment of lunar infrastructure is viewed not merely as a scientific milestone, but as a critical transition toward a

space-based economy where the Moon serves as a logistical and industrial platform for the broader exploration and commercialization of the solar system.

While perhaps perceived as less urgent by political actors, the scientific motivations underlying the contemporary lunar race are arguably the most critical regarding the long-term future of humanity. The Moon possesses the potential to serve as both an expansive, natural laboratory and a strategic staging ground for the manufacturing, monitoring, and maintenance of deep-space research missions extending beyond the Earth-Moon system. The pursuit of these objectives is expected to catalyze significant technological breakthroughs, precipitating a paradigm shift that will elevate various industrial sectors and civilian infrastructure to unprecedented levels of sophistication.

Finally, the exploration of the Moon is driven by existential imperatives essential for the continued social progress of humanity. A retrospective analysis of human history reveals a pattern of punctuated civilizational development characterized by significant evolutionary leaps. Following hundreds of millennia of relative isolation within Africa, the migration of early humans beyond the continent catalyzed a rapid transformation in both technological complexity and social stratification. For instance, the cataclysmic Toba supereruption, which nearly brought humanity to the brink of extinction, paradoxically facilitated global dispersal, leading to the emergence of the sophisticated Cro-Magnon culture and advanced lithic technologies after nearly two hundred thousand years of stagnation. Similarly, the Age of Discovery served as a primary catalyst for the Scientific Revolution, which ultimately forged modern civilization with its high-technology industrial base and democratic institutions. A compelling historical parallel can be observed in the evolution of Islamic civilization; the nomadic tribes of the Arabian Peninsula maintained a static social structure and rudimentary technology for millennia until the expansion of the Caliphate into a global empire. By engaging in trade and cultural exchange across the Old World, this civilization achieved a technological and scientific leap that surpassed Western capabilities for over five centuries. However, upon the cessation of exploratory, economic, and political expansion, the region entered a period of protracted stagnation that persists to the present day. Consequently, the expansion toward

the Moon and the establishment of permanent lunar settlements will inevitably trigger profound social and technological transfigurations within human civilization, ensuring its continued evolutionary momentum.

When planning permanent lunar outposts, the implementation of lunar agroecosystems becomes an indispensable requirement (Бондар і Хом'як, 2021). The primary objective of establishing such agroecosystems is to ensure operational autonomy, resilience, and a significant reduction in the lunar base's reliance on the exorbitant and inherently risky supply chains originating from Earth (Хом'як, 2021). Considering that the delivery of each kilogram of payload to the lunar surface incurs costs amounting to tens of thousands of dollars, the sustenance and atmospheric resources required for long-term crew habitation constitute a substantial portion of the logistical burden. The capacity to generate these resources in situ dramatically lowers the overall operational expenditures of the mission (Duri et al., 2022). Furthermore, agroecosystems facilitate the recycling of resources within a closed-loop framework, which is economically superior to continuous replenishment from Earth. A permanent settlement must remain resilient against disruptions in terrestrial supply chains, whether caused by geopolitical conflicts or technical launch failures; thus, a closed agroecosystem provides a critical threshold of independence essential for the survival of colonists. Through the process of photosynthesis, cultivated plants absorb carbon dioxide, and release oxygen, serving as a bioregenerative component within the life support system and reducing the mechanical and chemical load on life-sustaining hardware. While long-term missions typically rely on sublimated or preserved food supplies that suffer from nutritional degradation over time, the cultivation of fresh vegetables, fruits, and greens provides the crew with essential vitamins and micronutrients necessary for physiological health. Finally, the presence of living vegetation within the confined, isolated, and frequently hostile environment of a lunar base possesses profound psychological value. Tending to plants and observing their development functions as a potent mitigator of stress, bolstering crew morale through the phenomenon known as the «biophilia effect».

Since pedogenesis is an exceedingly protracted process (Zaets et al., 2011) requiring the active participation of diverse microbial consortia and other soil-dwelling pedobiota,

lunar agroecosystems will, for a considerable duration, function primarily through the mechanisms of substrate hydroponics (Keeter, 2022). Research indicates that lunar regolith, despite its total lack of organic matter and many essential mineral nutrients, can effectively serve as an inert hydroponic substrate or as a foundational component for synthesized soil mixtures (Baur et al., 1974). Utilizing in-situ regolith eliminates the logistical necessity of transporting vast quantities of terrestrial soil from Earth, thereby optimizing payload capacity for other critical mission hardware (Wamelink et al., 2014). The water required for these hydroponic systems can be sourced through advanced closed-loop recycling technologies or extracted from lunar water ice deposits, which have been identified in localized concentrations across the lunar surface. The empirical knowledge gained from the design, implementation, and long-term operation of these extraterrestrial agroecosystems will prove indispensable for the subsequent stages of human expansion, particularly as the distances from Earth become even more critical and the demand for total biological autonomy increases (Khomiak et al., 2024b).

The aim of this study is to assess the feasibility of utilizing lunar regolith derived from the surfaces of lunar maria as a hydroponic substrate within the agroecosystems of stationary lunar bases. To achieve this aim, the following objectives were set:

- To investigate the potential of using the lunar regolith simulant ETL-1 for cultivating selected varieties of the genus *Allium*.
- To model the potential for carbon dioxide absorption and biomass accumulation within the ETL-1 simulant when nutrients are not supplemented.
- To determine the overall viability of growing cultivated plants of the genus *Allium* using lunar regolith from the lunar seas as a hydroponic medium.

Materials and research methods

The ETL-1 lunar regolith simulant was utilized for the experimental phase of this investigation (Fackrell et al., 2024). The simulant was formulated from five discrete mass fractions of crushed tholeiitic basalt and quartz sand, with each fraction representing 20% of the total mixture by mass (Taylor et al., 2016). Notably, the quartz sand constituted 50% of the fifth fraction's mass, thereby accounting for 10% of the overall simulant mass (Fackrell, et al. 2024). Tholeiitic basalt fractions of the mud have the following sizes: 15-25 mm (5%),

5-15mm (5%), 2-5 (25%), 1-2mm (25%), <1 (25%). Quartz sand particles with a size of 0,2-1 mm constituted 10% by weight. The basalt component was pulverized via a mechanical impact process (employing a force range of 200–500), resulting in the formation of sharp-edged fragments of varying dimensions. The granulometric composition of the substrate was subsequently determined using a KP-131 sieve set (Rickman et al., 2007). Control trials were conducted using pure quartz sand.

Three species of cultivated plants were utilized for the experiment: «Gulyaipilsky» garlic, and «Stryhunivska» onion.

«Gulyaipilsky», or «Ukrainian White Gulyaipilsky», is a premium spring garlic cultivar originating from Ukraine, highly valued for its exceptional productivity and extended shelf life. This is a non-bolting type, which streamlines the cultivation process since no removal of flower scapes is required. Classified as a mid-season variety, its growth cycle typically spans 100 to 120 days. While primarily designated for spring planting, the cultivar exhibits adequate cold tolerance, enabling successful autumn sowing with reliable subsequent harvests. The yield potential is substantial, often reaching 5.0–5.5 tonnes per hectare, equivalent to an average productivity of 0.34 to 1.2 kg per square meter. The bulbs are dense and flattened-spherical in shape, usually weighing 20–37 grams, although weights up to 140 grams have been recorded. Small bulbs contain 6–10 cloves, while larger specimens may hold 12–16 cloves, each weighing 8–15 grams. A critical benefit is the variety's prolonged dormancy, allowing the harvest to be stored efficiently for 10 to 11 months (until the subsequent crop) with negligible quality degradation. Due to its proven resistance to agricultural threats such as nematodes and *Fusarium* wilt, the «Gulyaipilsky» cultivar presents itself as a promising biological resource for implementation in controlled, isolated environments, such as the agroecosystems projected for lunar and space stations.

Onion «Stryhunivska» is a mid-ripening, early-ripening, transportable variety. The growing season is 100-110 days. The bulbs are round and round-elongated, dense, weighing 80-100 g. Dry outer scales are light brown, inner ones are white. Onion *Stryhunivska* ripens well, stored for 7-8 months. Onion «Stryhunivska» is one of the main vegetable crops. It contains sugar, mineral salts, essential oil, vitamins. It is used in cooking in any form throughout the year. Onion «Stryhunivska» is a cold-resist-

ant, moisture-loving crop. Seeds germinate at $t^{\circ} +3-5^{\circ}\text{C}$ and therefore are sown early in spring. Sow as early as possible, since when sowing late, the seedlings are thinned, the bulbs do not ripen, and the yield is sharply reduced. Good results are obtained by sowing seeds before winter, before the soil freezes. Shoots appear 8-10 days earlier in such crops, the plants grow more intensively, and the onion ripens 12-15 days faster than when sown early in spring. Care for the crops consists of timely loosening of the soil, destruction of soil crust and weeds, formation of density and protection from pests and diseases. Formation of density begins when the second true leaf is formed.

The cultivation phase involved planting garlic and onion within both the experimental and control growth media, utilizing a single clove per trial replicate. Each substrate was carefully filled into 100 ml conical polyethylene containers to a uniform depth of 1 cm. To ensure optimal initial moisture levels, the cell surfaces were overlaid with a thin polyethylene membrane until the primary shoots emerged. Upon the appearance of the initial seedlings, the containers were transferred to a dedicated illuminated growth chamber. The photoperiod was set to 12 hours with a baseline light intensity varying from 2,000 to 5,000 lux. This intensity was subsequently augmented to a maximum of 30,000 lux for a 2-hour interval daily. The ambient temperature was strictly regulated: 18 $^{\circ}\text{C}$ during the darkness cycle and 23 $^{\circ}\text{C}$ during the illuminated period. Irrigation was performed twice daily at 9-hour intervals, using copious amounts of distilled water to saturate the media. Initial biomass measurements of the garlic and onion cloves/bulbs were recorded before planting using a Wi-cook WH-B05 electronic balance.

At the conclusion of the cultivation period, both the total plant biomass and the individual leaf masses were quantified. Throughout the observation phase, essential parameters such as plant height and leaf count were systematically documented. Statistical processing of the resulting data was conducted using Microsoft Math Solver, and the resulting growth patterns were visualized through graphical models generated in Microsoft Excel.

Research results

The cultivation of domesticated plant representatives from the genus *Allium* on the ETL-1 lunar maria regolith simulant has yielded remarkably promising results. Even in the absence of exogenous mineral supplement-

ation or the stabilization of nutrients within the substrate via organic polymers, such as humic acids, the plants exhibited consistent germination and sustained growth over an extended experimental period. Furthermore, the empirical data suggests a total absence of the acute phytotoxic or inhibitory effects previously associated with lunar stimulants; the ETL-1 material did not impede the initial stages of seedling development or the subsequent physiological vigor of the plants.

The initial emergence of sprouts for *Allium cepa* (cultivar «Strihunivska») was recorded on the 11th day, while *Allium sativum* (cultivar «Gulyaipilsky») exhibited germination on the 16th day. Comparatively, the onion specimens on the quartz sand control medium germinated one day earlier; however, this observation pertained only to the first 10% of individuals that formed shoots approximately 0.5 cm in height. Such a discrepancy may suggest statistical insignificance or environmental stochasticity, as analogous germination results were observed on the ETL-1 simulant within a subsequent 24-hour window. Mass germination occurred by the 18th day for the onion and the 16th day for the garlic. In the former case, an 80% germination rate was achieved, while the latter reached 50%. On the sand substrate, the results were comparatively lower, recorded at 60% and 30%, respectively. Despite the slower initial onset observed in the garlic, significant variations in shoot morphology were noted. During the phase of mass germination, the height of one-day-old *Allium cepa* shoots ranged from 1 cm to 6.6 cm (with early germinants reaching up to 11.2 cm), yielding an average of 4.9 cm. In contrast, *Allium sativum* exhibited a range between 3 cm and 6.5 cm (with early germinants reaching 12 cm) and an average of 4.6 cm. Performance on the control quartz sand was inferior; the height of one-day-old *Allium cepa* shoots fluctuated between 0.4 cm and 11.7 cm (with early germinants reaching 19.5 cm), though the average remained at 4.8 cm.

Active shoot development was observed over a duration of 43 days post-planting for the onion specimens and 45 days for the garlic. By the 43rd day, only 10% of the onion shoots continued to exhibit vertical growth, which subsequently ceased within the following 24-hour period. Morphological measurements at this stage revealed that the shortest onion specimens reached a height of 4.5 cm, while the tallest attained 34.5 cm, resulting in an overall mean value of 27.3 cm. During the

same timeframe, the garlic specimens demonstrated comparatively more modest developmental metrics; specifically, 60% of the individuals maintained active growth with a mean height of 9.8 cm, and total growth cessation occurred only three days later. In contrast, the onion seedlings cultivated on the control quartz sand exhibited a prolonged growth phase, with only 60% of the population having reached growth stasis by the 43rd day. The recorded shoot heights for the onion specimens in the sand control ranged from a minimum of 5.7 cm to a maximum of 36.2 cm, with a calculated mean height of 22.18 cm, indicating that while individual outliers were taller, the overall population performance was superior on the regolith simulant.

On the regolith simulant, the average daily growth rate for onion shoots fluctuated between 0.12 cm and 0.93 cm (with a mean daily increase of 0.67 cm), while on the quartz sand control, these values ranged from 0.19 cm to 1.01 cm (with a mean of 0.54 cm per day). Regarding the garlic specimens, the daily shoot growth on the regolith simulant varied from 0.14 cm to 0.35 cm (mean daily increase of 0.252 cm), whereas on the sand substrate, the growth rates ranged from 0.18 cm to 1.38 cm (mean of 0.18 cm per day).

Upon the conclusion of the experimental period, the total mass of the onion specimens cultivated on the ETL-1 regolith simulant ranged from 2 g to 7 g (with a mean mass of 3.9 g), while those on the sand substrate ranged from 1 g to 4 g (with a mean of 2.6 g). Notably, approximately 70% of the seedlings on the regolith and 20% of those on the sand exhibited a slight increase in mass attributable to the sequestration and transpiration of carbon dioxide. On the regolith, this mass gain averaged 1.4 g, although for 60% of the population, the increase was precisely 1 g. In contrast, a mass increase on the quartz sand was observed in only 20% of the seedlings, with an average gain of 1 g, further suggesting that the mineral composition of the ETL-1 simulant provides a more favorable environment for biomass accumulation and physiological development compared to the inert control.

Discussion

Since the success of seed and seedling germination on regolith or its various simulants is fundamentally contingent upon the availability of endogenous nutrient reserves and substrate moisture retention, the cultivation of representatives from the family Amaryllidaceae within extraterrestrial agroecosystems appears highly

promising (Ellery, 2021). These species possess the potential for multifunctional application in space habitats, serving as a primary source of nutritional sustenance, a biological medium for the adsorption of atmospheric carbon dioxide, and as foundational organisms within the long-term processes of planetary terraforming (Khomiak et al., 2024a). The evolutionary resilience of these taxa is further evidenced by their presence in disturbed or pioneer ecosystems on Earth (Черняєва і Хом'як, 2021), where they frequently act as primary colonizers in mineral-rich yet organic-poor substrates, mirroring the challenging conditions found in lunar or martian environments (Kozyrovska et al., 2006).

The ETL-1 lunar regolith simulant does not exhibit any aggressive or inhibitory phytotoxic effects on the seedlings; on the contrary, several developmental metrics indicate that the regolith-based substrate facilitates superior growth performance compared to the quartz sand control (Paul et al., 2022). Despite experiencing lower peak daily growth rates, the mean shoot height recorded on the regolith was consistently higher than that of the control group. Furthermore, a marginal increase in biomass was observed on the regolith—within the margin of error—attributable to carbon sequestration during the photosynthetic process. It can be hypothesized that the mineralogical composition of the basaltic simulant facilitates the leaching of specific macro- and micronutrients into the aqueous soil solution, including potassium, sodium, calcium, magnesium, phosphorus, and manganese (Gibson, 1977). While the concentrations of these liberated elements are insufficient to fully offset the depletion of the bulbs' endogenous chemical reserves during the intensive growth phase, their presence is significantly more pronounced than in the triple-washed quartz sand. This mineralogical disparity accounts for the observed variations in plant mass changes and confirms the potential of lunar maria regolith to serve as a partially bio-active substrate in extraterrestrial agricultural systems.

The potential threat posed by the radioactivity of lunar regolith, to which certain plant species exhibit sensitivity, remains relatively low. The radio-sensitivity of onions LD_{50} ranges between 100–150 Gy, while the absolute lethal dose LD_{100} is approximately 250 Gy. These figures represent moderate tolerance levels, comparable to the radio-sensitivity observed in lettuce and maize (Baur et al., 1974). Based on empirical data acquired from contempo-

rary lunar missions– specifically the German Lunar Lander Neutrons and Dosimetry (LND) instrument aboard the Chinese Chang'e-4 spacecraft – the cumulative radiation dose can be calculated with high precision. Throughout the vegetative period of the cultivars described herein, the accumulated dose is projected not to exceed 14 microsieverts. While this exposure level is approximately twice as high as the terrestrial background radiation, it is insufficient to exert a significant physiological impact on the cultivation of these crops. For contextual comparison, this dosage is equivalent to a single computed tomography (CT) scan and remains significantly lower than the annual exposure limits established for nuclear power plant personnel.

Conclusions

The lunar regolith simulator of the lunar seas ETL-1 does not show an aggressive or suppressive effect on seedlings. The first sprouts appear on the 16th day for garlic of the “Gulyaipilsky” variety and onions on the 11th day for onions of the “Strihunivska” variety.

The growth of *Allium cepa* shoots continues for 43 days from the moment, and 45 days for *Allium sativu* shoots. The average height of shoots at the end of the experiment for onions on the regolith simulator is 27.3 cm, and 10.21 for garlic.

The observations allow us to hypothesize that the presence of some mineral nutrition elements in the regolith leads to their entry into the aqueous solution, which partially compensates for the loss of chemical substances of the bulb spent on growth.

Bibliography

- Baur P.S., Clark R.S., Walkinshaw C.H., Scholes V.E. Uptake and translocation of elements from Apollo 11 lunar material by lettuce seedlings. *Phyton*. 1974. Vol. 32. P. 133–142.
- Duri L.G., Caporale A.G., Roupheal Y., Vingiani S., Palladino M., De Pascale S., Adamo, P. The potential for lunar and martian regolith simulants to sustain plant growth: a multidisciplinary overview. *Frontiers in Astronomy and Space Sciences*. 2022. Vol. 8. P. 747821. <https://doi.org/10.3389/fspas.2021.747821>.
- Ellery A. Supplementing closed ecological life support systems with in-situ resources on the moon. *Life*. 2021. Vol. 11, no. 8. P. 770. <https://doi.org/10.3390/life11080770>.
- Fackrell L.E. Humphrey S., Loureiro R., Palmer A.G., Long-Fox, J. Overview and recommendations for research on plants and microbes in regolith-based agriculture. *npj Sustainable Agriculture*. 2024. Vol. 2, no. 1. P. 15. <https://doi.org/10.1038/s44204-024-00109-7>.
- Ferl R.J., Paul A.L. Lunar Plant Biology– A Review of the Apollo Era. *Astrobiology*. 2010. Vol. 10. P. 261–274. <https://doi.org/10.1089/ast.2009.0416>.
- Gibson E.K. Volatile elements, carbon, nitrogen, sulfur, sodium, potassium and rubidium in the lunar regolith. *Phys Chem Earth*. 1977. Vol. X. P. 57–62.
- Keeter B. Scientists grow plants in lunar soil. Ed. Bill Keeter. NASA (*National Aeronautics and Space Administration*) 2025 [Електронний ресурс]. URL: <https://www.nasa.gov/feature/biological-physical/scientists-grow-plants-in-soil-from-the-moon> (дата звернення: 15.07.2025).
- Khomiak I.V., Onyshchuk I.P., Vasylenko O.M. Theoretical basis of classification of terraforming methods. *Екологічна наука*. 2024a. №4(55). С. 234–237. <https://doi.org/10.32846/2306-9716/2024.eco.4-55.38>.
- Khomiak I., Onyshchuk I., Khomiak O. Analysis of the relevance of astroecological research. *Екологічна наука*. 2024b. № 2. С. 35–38. <https://doi.org/10.32846/2306-9716/2024.eco.2-53.5>.
- Kozyrovska N.O., Lutvynenko T.L., Korniiichuk O.S., Kovalchuk M.V., Voznyuk T.M., et al. Growing pioneer plants for a lunar base. *Advances in Space Research*. 2006. Vol. 37. P. 93–99. <https://doi.org/10.1016/j.asr.2005.07.085>.
- Paul A.L., Smith D.P., Gigis P.J., Ferl J.B., Ferl R.L. Plants grown in Apollo lunar regolith present stress-associated transcriptomes that inform prospects for lunar exploration. *Communications Biology*. 2022. <https://doi.org/10.1038/s42003-022-03513-z>.
- Rickman D., McLemore C. A., Fikes J. *Characterization summary of JSC-1A bulk lunar mare regolith simulant*. 2007 [Електронний ресурс]. URL: http://www.orbitec.com/store/JSC-1A_Bulk_Data_Characterization.pdf ; http://www.orbitec.com/store/JSC-1AF_Characterization.pdf (дата звернення: 17.12.2025).
- Taylor L., Pieters C., Britt D. Evaluations of lunar regolith simulants. *Planetary and Space Science*. 2016. Vol. 126. P. 1–7. <https://doi.org/10.1016/j.pss.2016.03.015>.
- Wamelink G.W., Frissel J.Y., Krijnen W.H.J., Verwoert M.R. Can Plants Grow on Mars and the Moon: A Growth Experiment on Mars and Moon Soil Simulants. *PLOS One*. 2014. Vol. 9, no. 8. e103138. <https://doi.org/10.1371/journal.pone.0103138>.

Zaets I., Burlak O., Rogutskyy I., Vasilenkoa A., Mytrokhyn O., et al. Bioaugmentation in growing plants for lunar bases. *Advances in Space Research*. 2011. Vol. 47. P. 1071–1078. <https://doi.org/10.1016/j.asr.2010.05.011>.

Бондар С.С., Хом'як І.В. Терактрансформаційні стратегії освоєння незаселених субстратів. *Сталий розвиток країни в рамках Європейської інтеграції* : тези Всеукраїнської науково-практичної конференції здобувачів вищої освіти здобувачів вищої освіти і молодих учених. Житомир : ЖДТУ, 2021. С. 16.

Хом'як І.В. Глобальні екологічні проблеми з точки зору астроекології. *Екологічні науки*. 2021. № 6 (39). С. 154–157. <https://doi.org/10.32846/2306-9716/2021.eco.6-39.26>.

Черняєва О. П., Хом'як І. В. Терактрансформаційний потенціал *Elymus repens* (L.) Gould. *Сталий розвиток країни в рамках Європейської інтеграції* : тези Всеукраїнської науково-практичної конференції здобувачів вищої освіти і молодих учених. Житомир : ЖДТУ, 2021. С. 18.

References

Baur, P.S., Clark, R.S., Walkinshaw, C.H., & Scholes, V.E. (1974). Uptake and translocation of elements from Apollo 11 lunar material by lettuce seedlings. *Phyton*, 32, 133–142 [in English].

Duri, L.G., Caporale, A.G., Roupael, Y., Vingiani, S., Palladino, M., De Pascale, S., & Adamo, P. (2022). The potential for lunar and martian regolith simulants to sustain plant growth: a multidisciplinary overview. *Frontiers in Astronomy and Space Sciences*, 8, Article 747821. <https://doi.org/10.3389/fspas.2021.747821> [in English].

Ellery, A. (2021). Supplementing closed ecological life support systems with in-situ resources on the moon. *Life*, 11(8), Article 770. <https://doi.org/10.3390/life11080770> [in English].

Fackrell, L.E., Humphrey, S., Loureiro, R., Palmer, A.G., & Long-Fox, J. (2024). Overview and recommendations for research on plants and microbes in regolith-based agriculture. *npj Sustainable Agriculture*, 2(1), Article 15. <https://doi.org/10.1038/s44204-024-00109-7> [in English].

Ferl, R.J., & Paul, A.L. (2010). Lunar Plant Biology– A Review of the Apollo Era. *Astrobiology*, 10(2), 261–274. <https://doi.org/10.1089/ast.2009.0416> [in English].

Gibson, E.K. (1977). Volatile elements, carbon, nitrogen, sulfur, sodium, potassium and rubidium in the lunar regolith. *Physics and Chemistry of the Earth*, 10, 57–62 [in English].

Keeter, B. (2025, May 12). *Scientists grow plants in lunar soil*. NASA (National Aeronautics and Space Administration). [Electronic resource] URL: <https://www.nasa.gov/feature/biological-physical/scientists-grow-plants-in-soil-from-the-moon> (access date 15.07.2025) [in English].

Khomyak, I.V., Onyshchuk, I.P., & Vasylenko, O.M. (2024a). Theoretical basis of classification of terraforming methods. *Ekolohichni nauky [Ecological sciences]*, 4 (55), 234–237. <https://doi.org/10.32846/2306-9716/2024.eco.4-55.38> [in English].

Khomyak, I., Onyshchuk, I., & Khomyak, O. (2024b). Analisys aktual'nosti astroekolohichnykh doslidzhen [Analysis of the relevance of astroecological research]. *Ekolohichni nauky [Ecological sciences]*, (2), 35–38. <https://doi.org/10.32846/2306-9716/2024.eco.2-53.5> [in English].

Kozyrovska, N. O., Lutvynenko, T. L., Korniihuk, O. S., Kovalchuk, M. V., Voznyuk, T. M. & Kordium, V. A. (2006). Growing pioneer plants for a lunar base. *Advances in Space Research*, 37(1), 93–99. <https://doi.org/10.1016/j.asr.2005.07.085> [in English].

Paul, A. L., Smith, D. P., Gigis, P. J., Ferl, J. B., & Ferl, R. L. (2022). Plants grown in Apollo lunar regolith present stress-associated transcriptomes that inform prospects for lunar exploration. *Communications Biology*, 5(1), Article 869. <https://doi.org/10.1038/s42003-022-03513-z> [in English].

Rickman, D., McLemore, C. A., & Fikes, J. (2007). *Characterization summary of JSC-1A bulk lunar mare regolith simulant*. ORBITEC. [Electronic resource] URL: http://www.orbitec.com/store/JSC-1A_Bulk_Data_Characterization.pdf and http://www.orbitec.com/store/JSC-1AF_Characterization.pdf (access date 17.12.2025) [in English].

Taylor, L., Pieters, C., & Britt, D. (2016). Evaluations of lunar regolith simulants. *Planetary and Space Science*, 126, 1–7. <https://doi.org/10.1016/j.pss.2016.03.015> [in English].

Wamelink, G.W.W., Frissel, J.Y., Krijnen, W.H.J., & Verwoert, M.R. (2014). Can plants grow on Mars and the Moon: A growth experiment on Mars and Moon soil simulants. *PLOS One*, 9(8), e103138. <https://doi.org/10.1371/journal.pone.0103138> [in English].

Zaets, I., Burlak, O., Rogutskyy, I., Vasilenkoa, A., Mytrokhyn, O., & Kozyrovska, N. (2011). Bioaugmentation in growing plants for lunar bases. *Advances in Space Research*, 47(6), 1071–1078. <https://doi.org/10.1016/j.asr.2010.05.011> [in English].

Bondar, S.S., & Khomyak, I.V. (2021). Teratransformatsiyni stratehii osvoyennya nezaselenykh substrativ [Terratransformational strategies for the development of uninhabited substrates]. In *Stalyy rozvytok krayiny v ramkakh Yevropeyskoyi intehtratsiyi* [Sustainable development of the country within the framework of European integration]. Zhytomyr State Technological University. 16. [in Ukrainian].

Khomyak, I. V. (2021). Hlobal'ni ekolohichni problemy z tochky zoru astroekolohiyi [Global environmental problems from the perspective of astroecology]. *Ekolohichni nauky [Ecological Sciences]*, 6(39), 154–157. <https://doi.org/10.32846/2306-9716/2021.eco.6-39.26> [in Ukrainian].

Chernyayeva, O.P., & Khomyak, I.V. (2021). Teratransformatsiynnyu potentsial *Elymus repens* (L.) Gould [Terratransformational potential of *Elymus repens* (L.) Gould]. In *Stalyy rozvytok krayiny v ramkakh Yevropeyskoyi intehtratsiyi* [Sustainable development of the country within the framework of European integration]. Zhytomyr State Technological University. 18 p. [in Ukrainian].

Дата першого надходження статті до видання: 31.12.2025
Дата прийняття статті до друку після рецензування: 03.02.2026
Дата публікації (оприлюднення) статті: 31.03.2026

Стаття поширюється на умовах
ліцензії відкритого доступу (CC BY 4.0)

