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PROSPECTS AND RISKS OF USING LUNAR REGOLITH TO FORM ISOLATED ECOSYSTEMS

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The study investigates the potential for cultivating agricultural crops in lunar regolith from the lunar seas. The research utilized the ETL-1 lunar regolith simulant, "Celesta F1" radish seeds, "Gulyaipilsky" garlic cloves, and "Lidiya" peppermint rhizomes. Control experiments were conducted on pure quartz sand and the universal potting soil mix "Eco plus, Peatfield". The aim of the work is to explore the potential of lunar regolith as an edaphic basis for isolated ecosystems within future lunar bases. In line with this aim, the following objectives were set: to study the potential of using the ETL-1 lunar regolith simulant for crop germination; to model the potential for spontaneous ecosystem transformations with the ETL-1 lunar regolith simulant as the edaphic basis; to predict the dynamics of agroecosystem processes using the ETL-1 lunar regolith simulant as the edaphic basis. The ETL-1 lunar regolith simulant is capable of supporting the germination of seeds and the initial development of seedlings (from bulbs or rhizomes) for a short period. A correlation exists between the nutrient reserves in the seeds or seedlings and their growth performance on the ETL-1 lunar regolith simulant. The low albedo and granulometric structure of the lunar regolith result in water loss while simultaneously promoting its retention within the substrate's capillary structure. Untreated regolith, without the addition of mineral nutrients to the irrigation system, is suitable for growing short-season crops primarily for young sprouts (microgreens). Furthermore, regolith is susceptible to colonization by microorganisms, including pathogenic bacteria and fungi. There is also a risk of introducing aggressive weed seeds into the regolith system.

Key words: *invasive species, self-renewal of vegetation, Moon colonization, astroecoogy.*

ПЕРСПЕКТИВИ ТА РИЗИКИ ВИКОРИСТАННЯ МІСЯЧНОГО РЕГОЛІТУ ДЛЯ ФОРМУВАННЯ ІЗОЛЬОВАНИХ ЕКОСИСТЕМ

І. В. Хом'як

Робота присвячена дослідженню потенціалу вирощування сільськогосподарських культур на місячному реголіті місячних морів. Для роботи використано симуляцію місячного реголіту ETL-1, насіння редиски «Селеста F1», зубчики часнику сорту «Гуляйпільський» та кореневища м'яти перцевої сорту «Лідія». Контрольний експеримент проводився на чистому кварцовому піску

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й універсальній ґрунтовій суміші "Eco plus, Peatfield". Метою роботи є дослідження потенціалу місячного реголіту як едафічної основи для ізольованих екосистем місячних баз. Відповідно до мети було поставлено такі завдання: провести дослідження потенціалу використання імітації місячного реголіту ETL-1 для пророщування сільськогосподарських культур; змоделювати потенціал спонтанних перетворень екосистем з едафічною основою симуляції місячного реголіту ETL-1; спрогнозувати процеси динаміки агроекосистем з едафічною основою симуляції місячного реголіту ETL-1. Симулятор місячного реголіту ETL-1 здатний забезпечити проростання насіння та саджанців у вигляді цибулини або кореневища та підтримувати їхній розвиток протягом короткого часу. Існує залежність між запасами поживних речовин у насінні чи саджанцях та показниками їхнього росту на симуляторі місячного реголіту ETL-1. Низьке альбедо та гранулометрична структура місячного реголіту призводять до втрати води, її перебування в капілярній структурі субстрату. Реголіт без обробки та додавання в систему зрошення мінеральних елементів живлення придатний для вирощування культур з коротким часом вегетації заради молодих проростків (мікрозелені). Реголіт є вразливим для заселення мікроорганізмами, зокрема й патологічними бактеріями та грибами. Також існує ризик занесення на реголіт насіння злісних бур'янів.

Ключові слова: *інвазійні види, самовідновлення рослинності, колонізація Місяця, астроекологія.*

Introduction

The second decade of the 21st century can be characterized as the beginning of a new race for lunar exploration. The first Moon Race, which spanned from 1957 to 1975, was a political competition between the USA and the USSR. The current competition is economic and strategic in nature.

The Moon is now viewed as a promising industrial base, a source of rare mineral resources, and a reliable monitoring platform for research. It offers far greater potential for these functions than existing orbital stations. This is primarily due to the availability of a large number of materials that can be used for the station's construction and operation, as well as for manufacturing (Хом'як, 2021). Recent successes in thermonuclear energy have generated heightened interest in minerals containing ^3He. On Earth, it is present in very small quantities, with only a few grams being extracted annually. The surface layers of the lunar regolith, however, contain significantly higher concentrations. Despite intense debate regarding the practical feasibility and commercial viability of utilizing these minerals, the USA, China, Russia, India, Japan, EU nations, and many others have commenced active preparations for lunar colonization (Khomiak et al., 2024b).

In 2020, the governments of the USA, Australia, Canada, Japan, Luxembourg, Italy, the United Kingdom, the United Arab Emirates, Ukraine, and Brazil signed an agreement on the coordination of efforts in lunar exploration. The accord outlines the principles of cooperation in the civilian research and peaceful use of the Moon, Mars, comets, and asteroids. Current national and international programs driving this effort include the Artemis and CLPS (Commercial Lunar Payload Services) initiatives in the USA, Chang'e in China, Terrae Novae and Lunar Pathfinder in the EU, Chandrayaan and SLIM (Smart Lander for Investigating Moon) in India, and KPLO (Korea Pathfinder Lunar Orbiter) in South Korea.

The ultimate objective of these programs is the establishment of permanently operating research and production bases on the lunar surface. This goal is not a distant prospect; national schedules project the creation of these bases in the near future. Under the US Artemis program, this is anticipated by 2030, while the Sino-Russian ILRS (International Lunar Research Station) project is targeted for the 2031–2035 timeframe.

The initial, nominally research-oriented bases are projected to be established on the Moon by the end of the next decade. Subsequently, these will evolve into large-scale industrial centers, hosting dozens, potentially hundreds, of personnel. Oxygen and water can be provided to the inhabitants either from lunar minerals and rock processing or through comprehensive recycling systems. However, food will necessitate on-site cultivation or continuous supply from Earth. The latter, shipping food supplies to the Moon, would significantly escalate the overall production cost of all goods manufactured there.

The internal environments of these lunar bases align with Eugene Odum's definition of "Urban-industrial ecosystems". Consequently, all general processes governing the dynamics and functioning of these spaces will adhere to the fundamental principles of ecosystem theory (Бондар і Хом'як, 2021). Spontaneous ecological dynamic processes, which will require rigorous monitoring and control, are anticipated. These environments will comprise both residential and production areas conforming to Odum's industrial ecosystem classification, alongside agroecosystems that fall under the category of subsidized man-made ecosystems. The latter are intended to serve as the primary source of food provision for the station's inhabitants (Kozyrovska et al., 2006).

It can be hypothesized that the lunar bases will be situated in the circumpolar region of the near side of the Moon. Mare Frigoris is considered an ideal location by many experts. It is composed of rocks highly analogous to terrestrial basalts. The surface is covered by regolith, and only on very steep crater walls and within lava tubes do native bedrock formations occasionally outcrop.

The regolith formed over 4.6 billion years due to continuous bombardment by micrometeorites, solar radiation, and extreme temperature fluctuations. Impact destruction and subsequent melting, followed by rapid freezing, create sharp-edged, glassy agglutinates, somewhat resembling terrestrial tektites. In the lunar seas, the regolith layer can reach a depth of 4–5 meters. Notably, mare regolith exhibits a higher content of basalt, fully analogous to its terrestrial counterpart.

The regolith is composed of coarse grains, up to 1 cm in diameter, and lunar dust, the majority of which has a diameter less than 1 mm. It is dominated by oxygen and silicon, with a significant presence of iron, calcium, aluminium, and magnesium. Unlike terrestrial sedimentary rocks, iron in the lunar regolith exists in the Fe0 and Fe +2 oxidation states due to the absence of prolonged contact with high concentrations of oxygen and water. This characteristic further links the mare regolith to terrestrial basalt. The primary distinction is the high mass fraction of FeO (ferrous oxide) in lunar regolith, which reaches 17−22% (Gibson, 1977).

Lunar regolith is being considered as a potential construction material and a substrate for cultivating plants (Baur et al., 1974). Preliminary research has demonstrated both the potential for such applications and the inherent challenges. The main difficulties include the separation of regolith components by particle size, the oxidation of iron, and the removal of heavy metals. Furthermore, there is a risk of spontaneous colonization by organisms in such substrates. These include various microorganisms and, in the future, potential pest species for cultivated crops or parasites directly hazardous to human health.

The experimental investigation of processes occurring within ecosystems that utilize lunar regolith as their edaphic foundation is a highly relevant task in modern astroecology. A critical need for conclusions based on this research may arise within the next decade (Wamelink et al., 2014).

Currently, lunar regolith simulants are employed for these experiments. One of the most popular simulants today is JSC-1 (Johnson Space Center Number One) (Rickman et al., 2007). Regolith simulants are typically identified by three-letter acronyms indicating the organization that developed or distributes them. Many of these simulants face criticism for their low fidelity to the original material. For instance, Larry Taylor has highlighted issues concerning the lack of quality control and inflated pricing (Taylor et al., 2016).

This study aims to investigate the potential of lunar regolith as an edaphic basis for isolated ecosystems within future lunar bases.

In accordance with this aim, the following objectives were established:

– To research the potential of utilizing the ETL-1 lunar regolith simulant for the germination of crops.

– To model the potential for spontaneous transformations of ecosystems utilizing the ETL-1 lunar regolith simulant as the edaphic basis.

– To forecast the processes of agroecosystem dynamics with the ETL-1 lunar regolith simulant serving as the edaphic basis.

Material and methods

The ETL-1 lunar regolith simulant was employed for the experimental phase of this study. This simulant comprised five distinct mass fractions of crushed tholeiitic basalt and quartz sand (Table 1). Each fraction constituted 20% of the mixture by mass. The quartz sand component accounted for 50% of the fifth fraction's mass, translating to 10% of the total simulant mass (Fackrell et al., 2024).

The basalt was pulverized using a mechanical impact method (with a force range of 200−500 N), which yielded sharp-edged fragments of varying sizes. The granulometric composition of the substrate was determined using a KP-131 sieve set. Control experiments were executed using pure quartz sand and the universal soil mixture "Eco plus, Peatfield".

Three species of cultivated plants were utilized for the experiment: "Gulyaipilsky" garlic, "Lidiya" peppermint, and "Celesta F1" radish.

Table 1

Composition of the ETL-1 lunar regolith simulator

Rock	Fragment diameter (mm)	Mass fraction (%)
Tholeiitic basalt	15–25	5
Tholeiitic basalt	5–15	5
Tholeiitic basalt	2–5	25
Tholeiitic basalt	1–2	25
Tholeiitic basalt	<1	25
Quartz sand	0,2–1	10

"The "Gulyaipilsky" garlic (alternatively known as Ukrainian White Gulyaipilsky) is a versatile, high-yielding spring variety of Ukrainian selection, distinguished by its excellent long-term storage capacity and non-bolting characteristic. Although typically considered a spring variety, it tolerates autumn planting well and produces satisfactory yields. It is a mid-season variety with a vegetation period of 100–120 days. This garlic variety demonstrates high productivity, yielding up to 5–5,5 tonnes per hectare (or 0,34–1,2 kg/m^2). The bulb is flattened-round and dense, with an average weight of 20–37 g, though larger specimens can reach 140 g. Each bulb contains 6–10 cloves in smaller examples and 12–16 cloves in larger ones, with individual cloves weighing 8–15 g. A key feature is its non-bolting nature, which significantly simplifies cultivation as scapes do not require removal. It exhibits excellent dormancy; well-cured bulbs can be stored for 10–11 months (until the new harvest) with minimal loss of quality. The variety shows good resistance to some common diseases, such as nematodes and Fusarium wilt, making it a viable candidate for planting in the isolated agroecosystems of lunar space stations.

The «Lidiya» peppermint variety is a hybrid distinguished by a pronounced citrus note in its flavor and aroma. This perennial, spicy-aromatic herbaceous plant is widely utilized in culinary applications, beverages, and for medicinal purposes. The shrub is branched and upright, frequently forming dense clumps, reaching a height of 40–50 to 80 cm. Stems are quadrangular, greenish with a slight violet tint along the edges. The leaves are large, ovate or oval-lanceolate with serrated margins, and a rich dark-green color. The horizontally oriented rhizome ensures rapid spreading and the formation of dense stands. The period until the first harvest is approximately 25–30 days after emergence. The plant prefers partial shade but can tolerate full sun provided there is adequate irrigation. In intense sunlight, the leaves may become less succulent, whereas in deep shade, the plant tends to become etiolated. It thrives in fertile, moist, and well-drained soils, necessitating regular and ample watering, particularly during hot periods. The species is prone to aggressive proliferation via its rhizomes. To control its spread in a garden setting, the use of root barriers or container cultivation is recommended. Conversely, its propagation capability via the rhizome makes it a promising candidate species for the terraforming of colonized planetary bodies (Khomiak et al., 2024a).

The "Celesta F1" radish variety is an extra-early and highly adaptable hybrid of Dutch breeding (Enza Zaden), recognized as one of the most reliable varieties for all-season cultivation. It is valued for its rapid maturation and high resistance to adverse conditions. This hybrid (F1), which is of the round or Sora type, is very early-maturing, with harvests achievable 20–25 days after mass emergence. It can be cultivated successfully across any season, from early spring through autumn. Yields typically range from 30–40 t/ha (or 3–4 kg/m^2). The root shape is round or oblate-spherical, with a diameter of 3–4 cm. The average root weight is 20–25 g, reaching a maximum of 30–35 g. The root is bright, saturated red with thin, smooth skin; the color remains stable after washing. Internally, the structure features a snow-white, crisp, and succulent flesh. The root does not coarsen or develop pithiness or internal fissures, even when overgrown or subjected to stress. The cultivation of radishes and other cultivated cruciferous species has a long history of research under microgravity conditions. The primary advantages of the "Celesta F1" hybrid lie in its high plasticity and resistance to external stressors. The species exhibits strong resistance to bolting (stem formation) and cracking. It possesses high field resistance to downy mildew (Peronospora) and slimy bacteriosis. This species is well-studied, having been investigated both aboard the Mir Space Station and the International Space Station (ISS).

For the experimental procedure, garlic was planted in the experimental and control substrates using one clove per replicate. Peppermint was planted using rhizome fragments 2–3 cm in length, each containing a single bud. Radish was sown using one seed per replicate. The substrates were placed in 100 ml conical polyethylene cells at a depth of 1 cm. Until the emergence of the first shoots, the cells were covered with a thin polyethylene film to maintain humidity. After emergence, the plants were transferred to a lighted location. Illumination levels fluctuated between 2,000 and 5,000 lux over a 12-hour photoperiod, with an increase to 30,000 lux for a 2-hour interval each day. The temperature was maintained within a range of 18 °C (dark period) to 23 °C (light period). The substrate was heavily irrigated with distilled water twice daily at 9-hour intervals.

During the observation period, plant growth metrics (such as height) and the number of leaves were recorded. The resulting data underwent statistical analysis using Microsoft Math Solver, with graphical growth models constructed in Microsoft Excel.

Results

The study's findings demonstrated variations in both the timing of initial emergence and the rates of subsequent development and senescence (die-off). Significant differences were also observed between the experimental group and the first and second control groups.

The initial sprouts of *Raphanus sativus* variety "Celesta F1" emerged five days post-planting in both the soil and quartz sand substrates. This is consistent with the varietal characteristics, which specify an emergence period of 3–7 days, typically occurring within 3−5 days at temperatures ranging from +15 to +20 °C. Conversely, the regolith simulant exhibited a delay in germination, with emergence occurring only after eight days. This delay can be attributed to differences in the capillary and gravitational water cycling mechanisms across the substrates. Soil possesses multiple components, including appropriately sized particles and polymers like humic acids, that enhance moisture retention. While quartz sand lacks these retention mechanisms and functions as a well-drained substrate, it benefits from a high albedo (0,45), resulting in less intensive solar heating.

The regolith simulant, despite its finer particles, exhibits a tendency for its smallest fraction (mean size 27 μm) to cement together. This characteristic, while potentially beneficial for the future construction of lunar bases, presents a challenge for the use of unprocessed regolith in plant cultivation. The low albedo of basalt (ranging from 0,11 to 0,12) promotes its exacerbated heating. This combination of fragment cementation and strong solar heating contributes to moisture loss under the chosen irrigation regime.

The initial sprouts of *Allium sativum* variety "Gulyaipilsky" emerged on the 16th day. Emergence was observed across both control and experimental plots. The primary difference was in the germination rate (quantity of plants that sprouted): 100% success in the soil substrate, 30% in the sand, and 50% in the regolith simulant. In this particular scenario, moisture was not the governing factor, as the cloves possessed sufficient internal reserves. The key variables were the interaction between heat and humidity. Although the moisture content of the sand decreased to levels comparable to the regolith, the sand's temperature was also lower.

A similar trend was observed in the *Mentha piperita* experiment. Initial emergence occurred on the sixth day. However, the percentage of successful sprouting was 80% in the soil, 60% in the sand, and only 50% in the regolith simulant. Two weeks later, this distribution shifted to 90, 70, and 50%, respectively. All plants experienced significant overgrowth (senescence onset) in the soil only after 21 days. Conversely, sprouts in both the sand and regolith simulant began to die off. Only 20% of the living individuals remained in the sand, while all individuals in the regolith simulant perished.

Regarding the change in sprout dimensions, several non-linear patterns were observed. In the sand substrate, 100% of *Raphanus sativus* seeds germinated, with the mean sprout height on the first day of observation being 6,55 cm. Conversely, in the soil, only 80% of seeds had germinated by that day, with a mean height of 7,88 cm. Thus, the variety exhibited different germination rates in soil (80%) and sand (100%).

By the third week, the number of live individuals in the sand had decreased to 30%. Mean sprout size increased to 9,5 cm, with some individuals reaching 11,6 cm. By the fourth week, all individuals in both the sand and regolith simulant substrates had perished. In the regolith simulant, 80% of individuals had germinated by the third week, with a mean height of 1,1 cm. The highest germination success in the regolith was recorded on

Day 21 at 90% of individuals, with an average height of 1,5 cm.

The mean height of *Allium sativum* on the first day of emergence was 8,43 cm for 100% of seedlings in the soil, compared to 6,04 cm for 50% of seedlings in the regolith. By the experiment's conclusion (45 days), 40% of individuals remained viable in the sand (mean height 6,88 cm), 100% survived in the soil (mean height 16,64 cm), and 60% survived in the regolith simulant (mean height 9,8 cm).

For *Mentha piperita*, the mean size of new shoots at the onset of sprouting was 2,46 mm (soil), 1,45 mm (sand), and 7,8 mm (regolith simulant). At the point of maximum sprouting in the regolith simulant (Day 12), the soil maintained 100% viability (mean new shoot height 5,01 mm), the sand had 70% viability (mean height 3,72 mm), and the regolith simulant had 50% viability (mean height 9,12 mm). By Day 22, live individuals remained only in the soil substrate, where their height ranged from 6,5 to 13,5 cm until the end of the experiment. No live individual was recorded in the regolith simulant from Day 21 onwards.

This suggests that the regolith simulant is initially more conducive to the rapid development of *Mentha piperita* seedlings than either sand or soil, but it is incapable of providing sufficient essential nutrients for sustained growth.

Despite measures implemented to prevent the introduction of other species, a crust of cyanobacteria was observed on the regolith surface in some instances, alongside the germination of several weed species. These included *Galinsoga parviflora* Cav., *Portulaca oleracea* L., and *Sonchus arvensis* L.

Discussion

Experiments utilizing lunar regolith simulants, conducted by researchers since the original Moon Race, primarily sought to establish the absence of toxic effects on plant growth. Standard model organisms, such as *Arabidopsis thaliana* and *Tagetes patula*, were frequently employed (Paul et al., 2022). These early experiments indicated no significant negative impacts on the model organisms (Ferl & Paul, 2010).

In 2022, Bill Keeter reported on the germination of *Arabidopsis thaliana* using original lunar soil retrieved by the Apollo missions (Keeter, 2022). Although the plants successfully sprouted and developed into seedlings, they were not as robust as control samples grown in volcanic ash. Furthermore, the experiments revealed variations in plants grown in regolith based on the sample collection site: *Arabidopsis thaliana* grown in regolith from the Apollo 12 and Apollo 17 missions were more vigorous than those grown in samples from Apollo 11 (Baur et al., 1974).

Beyond hypothetical toxicity, other factors influence the potential of lunar regolith for crop cultivation. It is crucial to select only the regolith components that promote optimal capillary moisture formation. These particles should be analogous to terrestrial loess, yielding a mixture composed of particles sized 0,05 to 0,005 mm (up to 60%), less than 0,005 mm (up to 10–20%), and 0,1–0,25 mm (up to 7%). Coarser and finer particles could be repurposed for construction needs.

The irrigation system for the regolith substrate must account for its heating properties and granulometric composition. Watering should be more frequent, and water temperature should be adjusted based on the light regime. During periods of maximum insolation, the moisture volume should be higher and its temperature lower. Drip irrigation is recommended for operational agroecosystems.

A critical factor for growing crops in lunar regolith is the reserve of nutrients and moisture within the seeds and seedlings (Zaets et al., 2011). This reserve enables better tolerance of unfavorable environmental conditions. Nutrient stores are typically higher in bulbs and tubers than in rhizomes, simplifying their initial germination (Ellery, 2021). However, rhizomatous species hold significant promise for future terraforming efforts (Черняєва і Хом'як, 2021).

Even without supplementing the regolith with additional mineral substances, it is suitable for growing microgreens (Duri et al., 2022), primarily those that possess sufficient nutrient reserves in their seeds or vegetative propagules (bulbs, tubers, etc.). For cultivated plants with fine seeds, the use of classical hydroponic solutions is necessary.

The ability of regolith to temporarily support the function and development of higher vascular plants indicates its potential as a substrate for numerous lower organisms (Castro et al., 2004), notably algae, bacteria, and fungi. Among these, there may be species that pose a risk to cultivated plants and the health and life of human inhabitants (Kral et al., 2004).

Conclusions

The ETL-1 lunar regolith simulant is capable of supporting the germination of seeds and seedlings (from bulbs or rhizomes) and sustaining their initial development for a short duration.

A correlation exists between the internal nutrient reserves present in the seeds or seedlings and their subsequent growth metrics on the ETL-1 lunar regolith simulant.

The low albedo and specific granulometric structure of the lunar regolith lead to water loss while simultaneously promoting its retention within the substrate's capillary structure.

Unprocessed regolith, without the addition of mineral nutrients to the irrigation system, is suitable for cultivating short-season crops primarily for young sprouts, or microgreens.

The regolith is vulnerable to colonization by microorganisms, including pathogenic bacteria and fungi. Furthermore, a risk exists regarding the inadvertent introduction of aggressive weed seeds into the regolith substrate.

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