Lunar Regolith Unexpectedly Boosts Plant Growth

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Abstract

The ambitious goal of lunar habitation requires innovative solutions for sustainable food production. Lunar regolith, while abundant, poses challenges for plant growth due to its composition primarily the high silica content. The impracticality of transporting vast quantities of terrestrial soil to the lunar surface for large-scale cultivation necessitates new findings. This study investigated the potential of supplementing lunar regolith with terrestrial soil to support plant cultivation. rom the several lunar regoliths that were researched, the one designated by "Apollo 11" was selected based upon the possibility of future landing sites. Lunar regolith simulant was created. Raphanus raphanistrum (radish) seeds were planted and grown in various mixtures of lunar regolith and Earth soil. It was found that a small addition of Earth soil to the lunar regolith significantly enhanced plant growth compared to those grown solely in Earth soil ($p<0.05$). This breakthrough could revolutionize lunar agriculture, reducing the need for transporting vast amounts of terrestrial soil, which is both expensive and logistically complex. By minimizing the reliance on Earth-based resources, this approach could result in significant savings for food production. A limitation of this study is that it does not account for the gravity that would be experienced on the moon. Future research could focus on understanding the effects of low gravity on plant growth, expanding the range of crops tested to pave the way for sustainable extraterrestrial agriculture, observing plant health, survival rates, and nutrient uptake.

Keywords: **lunar regolith, plant growth, radish, moon space agriculture**

Introduction

Humans have long been captivated by the allure of space exploration, particularly the moon. The pursuit of lunar habitation faces a significant challenge: securing a reliable food supply. Transporting food or terrestrial soil from Earth is prohibitively expensive and logistically complex. For instance, establishing a 100 sq ft growing area for one person-year would require approximately 750 kg of soil, costing around $75 million to transport. To reduce this dependency on Earth-based resources, it's crucial to explore ways to utilize lunar regolith for plant growth.

Lunar regolith is a fine, unconsolidated material with distinct properties due to the moon's unique environment (Heiken et al., 1991). The dark maria, a region on the moon's surface, is composed of basalt, which is high in silica (Aderin-Pocock, 2019). Most lunar regolith varieties contain over 50% silica, giving it a sandy texture and reducing its nutrient content, making plant growth challenging (Paul et al., 2022; Wieger et al., 2014; Wamelink et al., 2014). While lunar regolith is rich in chemicals like Al2O3, CaO, and FeO (Horie et al., 2012), their individual effects on plant germination and growth are unknown. Previous studies have shown that plants grown in lunar regolith or its simulants experienced stunted growth and low survival rates (Paul et al., 2022; Wamelink et al., 2014). Consequently, current space-based agriculture efforts, such as those on the International Space Station, utilize Earth soil (NASA).

These studies demonstrate the difficulties of growing plants in lunar regolith without additional nutrients. Compost, a biologically active material formed through microbial decomposition of organic matter, can revitalize nutrient-deficient soils and promote plant growth. For example, adding approximately 33% compost by volume to degraded soil can improve its health and structure over time (Heyman et al., 2019). However, it is not known whether lunar regolith can be revitalized in a similar manner.

This study investigates the potential of supplementing lunar regolith with terrestrial soil to support the germination and growth of radish plants. Raphanus raphanistrum, a type of radish, being edible and a root plant, offers a more practical representation to be compared to other plants realistic for this project, as to other model plants like Arabidopsis thalina. Arabidopsis is a small flowering plant that has been of great interest since it was the first plant to have its entire genome sequenced. By supplementing lunar regolith with terrestrial soil, it may become feasible to transport smaller quantities of terrestrial material for plant cultivation on the moon.

Hypothesis

If supplementing lunar regolith with 25% of terrestrial soil enhances the growth of vegetable plants, then the need of Earth-derived material for lunar agriculture can be dramatically reduced. Since transporting material from Earth to the moon is expensive and logistically demanding, the findings would result in tremendous cost savings and simplify logistical challenges.

Independent Variable

The independent variable is the different percentages of lunar regolith (0%, 25 %, 50%, 75%, 100%) added to the soil and compost mixture in each pot.

Dependent Variable

The dependent variable is the height of each radish plant (including the root and plant lengths measured in cm).

Constant Variables, Control Group, Sample Size

The condition with 0% lunar regolith was the control group. The sample size was a minimum of five plants. The constant variables applied were the type and amount of compost, number of seeds in each pot, type of soil used, type of lunar regolith, and temperature of the growth chamber.

Materials

The experiment requires the following materials:

- Silica, used because it is a main constituent in lunar regolith

- Aluminum oxide, used because it is a main constituent in lunar regolith
- Titanium oxide, used because it is a main constituent in lunar regolith
- Calcium oxide, used because it is a main constituent in lunar regolith
- Iron oxide, used because it is a main constituent in lunar regolith
- Compost, used to help add nutrients and promote growth in the soil
- Soil, used leave each soil mixture to have the same weight without helping the plants to grow better like compost
- Seed starter pots, used to grow the plants
- Radish seeds, seed of choice to put in each pot
- One spray bottle filled with sitting tap water, used to water the plants
- Gloves, face mask, pair of goggles, used as a safety hazard to protect the scientist
- Weigh scale, used to weigh out compost, soil, lunar regolith, and chemicals
- Pair of tweezers, used to take out each plant carefully from its pot before measuring
- Seedling heat mat, used to create a moist and warm environment for the plants
- Stirring rod, used to make hole in the soil for the seeds and to mix the soil mixtures
- One plastic storage container with lid (approximately 34.63"L x 18.75"W x 12.63"H), used to store the plants and help keep a warm environment for them
- One small round plastic container with lid (approximately 1 ml capacity), used to create the lunar regolith and shake the components to ensure chemicals were mixed thoroughly
- Five transparent plastic cups (each big enough to cover a seed starter pot), used to cover the seed starter pots and keep the warm environment for the plants growing in the pots
- Notebook, pen, Sharpie, and ruler, used to collect data and measure plants

Safety

Standard laboratory procedures must be followed. Wear appropriate personal protective equipment, including long pants, closed-toe shoes, gloves, a lab coat, and eye goggles. To prevent chemical inhalation, wear a face mask. Dispose of waste chemicals in a designated chemical hazard disposal bag.

Methods

Preparation of lunar regolith.

Lunar regolith samples from various Apollo missions (NASA) were analyzed (Table 1.1). Due to its favorable landing site, "Apollo 11" regolith was selected. Individual chemical constituents were carefully weighed and combined in small containers. After a 24-hour settling period, the containers were opened to minimize the risk of inhalation. Different ratios of terrestrial soil and lunar regolith were then prepared (Table 1.2) and placed in seed starter pots.

Compositions of Lunar Regolith from Different Apollo Missions (%)	
	Apollo 11 (used in this study)
Silica (SiO_2)	47.2
Aluminum oxide (Al_2O_3)	14.3
Titanium oxide (TiO_2)	7.7
Calcium oxide (CaO)	13.2
Iron oxide (Fe_2O_3)	17.6

Table 1.1

Compositions of Soil Mixtures Used (g)								
Group	Compost	Soil	Lunar Regolith	Silica	Aluminum Oxide	Titanium Oxide	Calcium Oxide	Iron Oxide
0%	2	8	0	0	0	0	0	0
25%	2	6	2	1.89	0.57	0.308	0.53	0.7
50%	2	4	4	3.78	1.14	0.62	1.06	1.41
75%	2	2	6	5.66	1.72	0.92	0.79	2.11
100%	2	0	8	7.55	2.29	1.23	2.11	2.82

Table 1.2

Planting seeds.

1. Label each seed starter pot according to its lunar regolith concentration: 0% (control), 25%, 50%, 75%, and 100%.
2. Prepare the soil mixtures: Using a scale, tare the plastic cup, and add the appropriate amounts of compost, soil, and lunar regolith (Table 1.2). Mix thoroughly and pour into the corresponding pot. Wet the soil in each pot thoroughly (ensure that the water is not dripping from the soil), using a spray bottle.
3. Plant the radish seeds: Gently press five evenly spaced dimples into the soil in each pot. Clean the stirring rod after each use. Place one radish seed in each dimple, cover with a thin layer of soil, and water gently.
4. Create a warm and moist environment: Place the pots on a heating pad, cover them with plastic cups, and plug in the heating pad. Ensure the pots remain upright to maintain a consistent environment.

Observations and data collection

1. Monitor plant growth: Observe each pot daily to check the soil for dryness and general plant health. Water the plants gently with a spray bottle as needed.
2. Harvest plants: At the end of the growing period (6-7 days), wear personal protective equipment and carefully remove each plant from its pot using clean tweezers.
3. Measure plant growth: Measure the length of each plant's shoot and root in centimeters. Gently wash the roots in a bowl of water for more accurate measurements. Record your observations.

Statistical Methods

Statistical analysis was carried out using student's t-test on Microsoft Excel with $p<0.05$ considered significant.

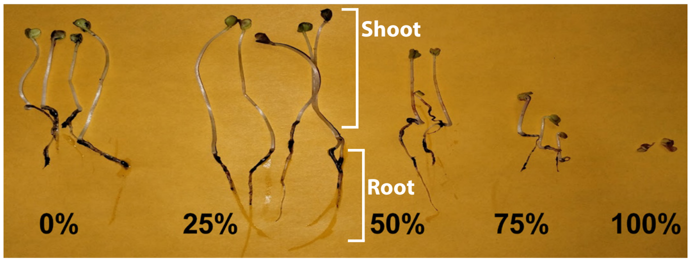

Fig. 1. Growth of plant shoot, root, and total length relative to the control group.

All groups exhibited seed germination but shoot and root development occurred in all groups except the 100% lunar regolith group (Figure 1). Plant growth was carefully monitored (Table 1.3). Since previous studies had indicated that lunar regolith slows the germination and growth of plants compared to that in Earth soil, it was expected that the lunar regolith would be detrimental to the growth of the plants (Wamelink et al., 2019). However, plants in the 25% lunar regolith group outgrew those in the control group (Earth soil) (Figure 2). While 50% lunar regolith yielded comparable growth to Earth soil, higher concentrations hindered plant development. An interesting data was to compare the relative growth in the different groups relative to that in the control group. It was clear that the plants in the 25% group outgrew the rest (Figure 3). Linear regression analysis revealed a strong correlation between total plant length and lunar regolith percentage, further supporting these findings (Figure 4). All results between different regolith groups and the control group were statistically significant ($p<0.05$).

Effect of Different % of Lunar Regolith on Shoot, Root, & Total Growth (cm). SE indicates the standard error of the mean. N=5 samples

	Shoot (mean)	Shoot (SE)	Root (mean)	Root (SE)	Total (mean)	Total (SE)
0%	5.5	0.7	2	0.7	7.5	1.4
25%	7.3	0.2	4	0.6	11.3	0.8
50%	3.2	0.8	3.5	1	6.7	1.8
75%	2.2	0.2	1.4	0.5	3.6	0.6
100%	0.5	0.3	0	0	0.6	0.3

Table 1.3

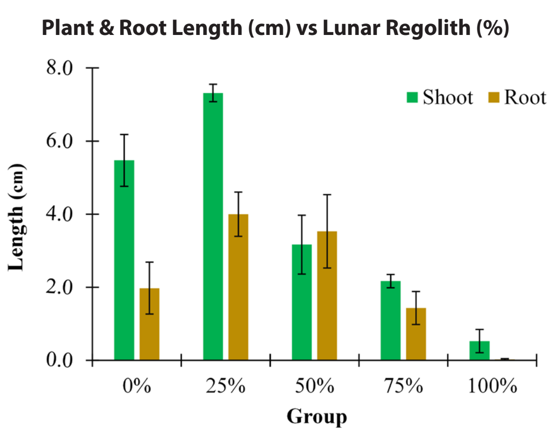

Fig. 2. Plant, shoot, and root length vs. percentage lunar regolith in the soil. The error bars indicate standard error of the mean.

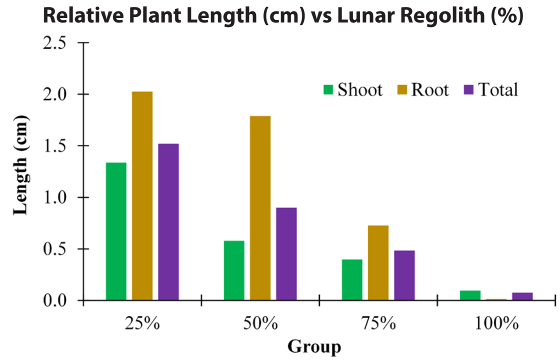

Fig. 3. Growth of plant shoot, root, and total length relative to the control group.

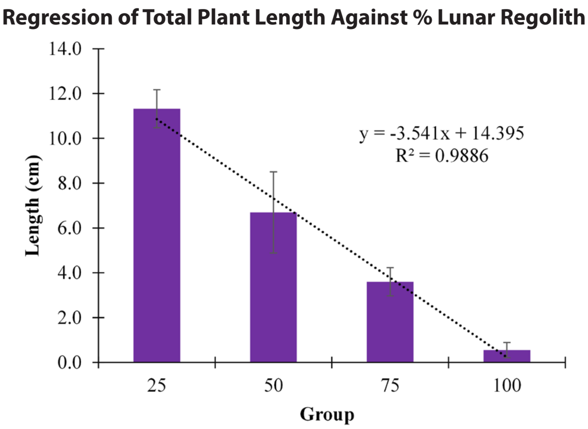

Fig. 4. Linear regression showing strong positive correlation of total plant length against the percentage of lunar regolith in the soil.

Discussion

This study presents a novel finding that supplementing lunar regolith with terrestrial soil and compost can not only support plant germination and growth but also accelerate it. The observation that plants in the 25% lunar regolith group outperformed the control group (terrestrial soil) suggests that the various chemicals in lunar regolith may be beneficial for plant growth. The growth in the 50% lunar regolith group was comparable to that in the control group. The results can be attributed to the beneficial effects of inorganic compounds, such as calcium oxide (White & Broadley, 2003), and iron oxide (Morrissey & Guerinot, 2010) on plant growth, particularly in nutrient-deficient soils. However, higher concentrations of these compounds can have detrimental effects on plant development, which was observed in conditions with higher amounts of the regolith. These results indicate that to attain the same growth in lunar regolith as in terrestrial soil, the amount of terrestrial soil transported to the moon can be lowered by 50%. This would significantly lower transportation costs, potentially saving up to $37.5 million per person-year (Figure 5).

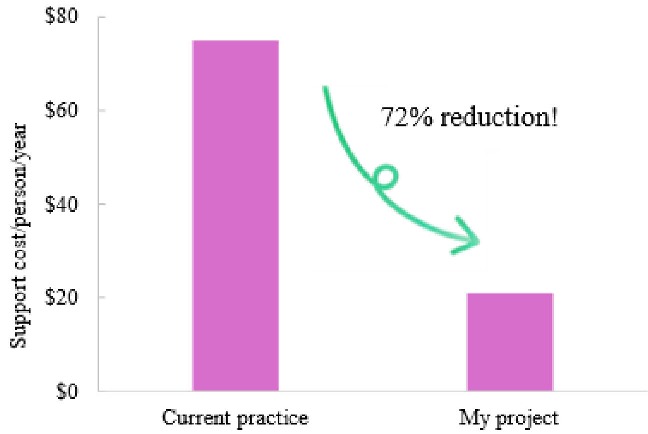

Fig. 5. Cost to transport soil to the moon to support one person/yr can be lowered by 50% or $37.5 million.

While the findings are encouraging, it is important to note several limitations. Our study did not account for the effects of reduced lunar gravity, which could impact plant growth and development. The study was limited to just one type of plant and future work could be expanded to additional plant types. Additionally, we did not assess the fruit-bearing potential or quality of the produce. It may also be interesting to determine how each individual component of the regolith affects plant growth. Finally, it would be valuable to determine if the plants experienced any stress under lunar conditions.

Despite these limitations, our results offer promising insights. The success of this approach on lunar regolith suggests its potential applicability to Martian regolith. Furthermore, our findings could be adapted to improve plant growth on Earth. By systematically optimizing the levels of various chemicals in the soil, we may be able to enhance agricultural yields and sustainability.

Conclusions

This study demonstrates the feasibility of utilizing lunar regolith for plant growth on the moon. These findings reveal that supplementing lunar regolith with both terrestrial soil and compost not only supports plant germination and growth but also accelerates it compared to terrestrial soil alone. This has significant implications for future lunar habitation, potentially reducing the amount of terrestrial soil needed for sustainable food production. Recent results have indicated that space-grown plants exhibit changes to density at the primary root tip compared to Earth-grown plants as well as higher stress (Bowlby, 2024). It is possible that supplementing the regolith with Earth soil as carried out in our study would address these issues. Lunar regolith contains several compounds that are essential for the growth of plants; adding terrestrial soil lowers the concentration of these compounds (Mazhar et al., 2024) and provides additional nutrients that helps plants grow. The results from our study suggest that lunar regolith may have the potential to support plant life and could facilitate future human exploration and settlement.

Overall, this study presents a significant advancement in the field of lunar agriculture. By demonstrating the potential of utilizing lunar regolith with proper conditioning, it opens new avenues for sustainable food production on the moon and contributes valuable knowledge to future space exploration endeavors.

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