MAXIMIZING PLANT GROWTH IN REGOLITH FOR LUNAR DAYS

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Plant the Moon Challenge Final Report

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Background

Humans and the Moon have a long-standing bond. While we marveled at it for centuries from afar, NASA's ambitious moon missions are putting it well within our reach for long term missions. As budding scientists, we are aspiring to facilitate future generations to become truly a multi-planet species. Equipping early lunar settlers and researchers to harness the moon's resources to become self-sustaining will enhance capabilities to lengthen mission durations and eventually successful inhabitation of the moon. Apart from problems associated with lack of a significant atmosphere while growing plants on the moon, humans must overcome several factors that can inhibit plant growth including the alkalinity, lack of nutrients, and moisture retention of the regolith. In addition, a unique challenge that is faced while growing plants on the Moon is the length of the lunar day. The lunar day is the period of time for the moon to complete one rotation on its axis with respect to the Sun and lasts for 29 days,12 hours and 44 minutes. During the length of the lunar day, the face of the moon locked to the earth's surface remains exposed to the sun for about 14 days and the other side is exposed to the sun for the next 14 days. Our project is focused on understanding factors that can potentially enhance plant yield during the lunar day.

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Maximizing yield of plants with nutritious value depends on strategic selection of plant species and identifying optimal growth conditions. Analysis of prior literature showed that choice of plant species was dependent on four key categories: speed of growth, space needed for growth, nutritional value, and resilience to harsh conditions. Garden cress excels in each of these categories. Cress grows quickly which provides humans quick crop yield after fifteen to twenty days and was vital for our experimentation. Cress is also known to be easy to plant, harvest and monitor. The plant's resistance to alkalinity and its ability to grow in confined spaces also served as key selection criteria. Cress is also very nutritious as it contains vitamin A, vitamin C and vitamin K. Hence, garden cress was selected as one of the most suitable plant for experimentation in regolith.

Experimental Design

Our experiment was conducted using a total of twelve (12) pots spread across three (3) growth sites. Each site had 4 pots - one control comprising 100% soil and three treatment mixes comprising varying mixes of regolith and soil. The ratio of soil to regolith across were as follows - one pot with 50% regolith and 50% soil, one pot with 62.5% regolith and 37.5% soil and one pot with 75% regolith and 25% soil. Total volume of soil or regolith soil mix was maintained at 600 ml across all pots. Two grams of cress seeds was soaked in paper towels for twenty-four (24) hours to promote germination, and then planted the resulting sprouts split equally across the four pots (Table 1).

Type (Treatment vs. Control)	**Mix Proportion (Soil to Regolith)**	**Percentage soil**	**Percentage Regolith**
Treatment	50-50	50.00	50.00
Treatment	37.5 - 62.5	37.50	62.50
Treatment	25-75	25.00	75.00

Control	100-0	100.00	0.00

Table 1: Regolith to soil proportion variation across control and treatment groups

To observe the plant yield under the conditions of the Moon's lunar day, the growth cycle was set at 28 days from date of planting. Visual growth confirmation was conducted daily. The plants were not invasively measured during the growth phase. Garden cress were harvested on day 28 and measured (root to tip) for weight and height.

Hypothesis

First, the goal of the Plant the Moon project was to understand the effects of using regolith as the growth medium. We believe that variations in the soil to regolith percentage will impact the plant yield. We hypothesized that there would be significant differences in plant yield (plant height and plant weight) based on the regolith- soil mix ratio. Beyond the mix proportions of soil and regolith, we sought to explore the key experimental parameters that can contribute to improving plant yield.

Independent Variables

Water: 30 ml of water added was varied across 3 levels – twice a day, daily and alternate days. Average moisture of both control and treatment mixes were recorded as moist (3.5 and 4) on the Rapitest digital meter.

Fertilizer: The regolith lacks many necessary nutrients that soil normally provides for plants like nitrogen. Thus, we added ***ammonium sulfate*** to our soil in order to accomplish both of these tasks at once. See Table 3. Ammonium sulfate lowers the pH of the regolith to healthy levels for the plants and provides them with an excess of nitrogen they desperately require. All 4 pots in site 1 received 0.25 cup mixed in 30 ml water in a single day. Fertilizer of 0.25 cup mixed in water and administered in 2 installments over a 2-day period in site 2. Two pots in site 3 received fertilizer, one pot received 0.375 cup mixed in 30 ml water and received 0.125 cup with 30 ml water. All fertilizer additions in site 3 was on a single day.

Light: The amount and intensity of sunlight accessible on the moon differs greatly from that of the Earth. A lunar day is 29.53 Earth days long or 708.7 hours consisting of 14.5 days of sunlight and 14.5 days of darkness (NASA). If sunlight from the moon was to be utilized, then the plants would require some form of shield to filter out harmful radiation. Hence, a lab setting where both light color and light intensity can be controlled would both simplify the growing experience for the plants and could be tailor made to fit the lighting needs of the individual species. According to a study conducted on the effect of different lights on plant growth, blue and red light is necessary for a better and more complete growth of plants. Many grow lights on the market today specialize in providing plants with these colors of light making them perfect for use in a moon setting especially if they can be compacted and stored easily.

Site Location 1		Site Location 2		Site Location 3	
Natural Light: NO		Natural Light: YES		Natural Light: NO	
Pot 1	Pot 4	Pot 2	Pot 5	Pot 3	Pot 6
Pot 7	Pot 10	Pot 8	Pot 11	Pot 9	Pot 12
Artificial Light: 400 lumens		Artificial Light: 400 lumens		Artificial Light: 600 lumens	
Week 1: light per day: 12 hrs		Week 1: light per day: 12 hrs		Week 1: light per day: 12 hrs	
Week 2: light per day: 9 hrs		Week 2: light per day: 12 hrs		Week 2: light per day: 9 hrs	
Weeks 3 & 4 : light per day: 6 hrs		Weeks 3 & 4: light per day: 12 hrs		Weeks 3 & 4: light per day: 9 hrs	

Table 2: Exposure to Natural and Artificial light during experimentation

We experimented with both lighting formats to determine the least wasteful and most effective one and also varied the duration of lighting to best match the conditions plants would face on the moon. We varied the length of exposure to natural light as well as lengths and intensity of grow light (Table 2). We changed the intensity, duration, and types of light sources. Pots 1, 4, 7 and 10 received 12 hours of 400 lumens of 40 watt red-blue light, while pots 3, 6, 9, and 12 received 12 hours of 600 lumens of 60 watt red-blue light. On the other hand, pots 2, 5, 8, and 11 received a combination of 24 hours of light: 12 hours of 400 lumens of 40-watt red light and 12 hours of sunlight. Having these different variables in the lights allowed us to study the effect of light intensities, durations, and the type of light on the growth of garden cress.

Dependent Variables:

Yield of garden cress was measured both in terms of plant height and harvested weight. While harvested plant is widely prevalent, plant height is an accepted measure to estimate crop yield or bio-mass.

Measurement:

During the growth phase, visual confirmation of plant growth and survival were completed on a daily basis. Plants were not subjected to any invasive measurement techniques, and also due to the brevity of their growth cycle. Plant growth was measured in terms of the mass and a stem height at the end of the growth period.

Controls:

Average room temperature was maintained between 68.5 – 70 F across the sites and average room humidity was recorded between 26 -29 % across the three site locations.

Average Humidity: The temperature affects the plant's processes, such as photosynthesis, transpiration, respiration and germination. In our experiment, the temperature was held at 18-22 degrees Celsius. This temperature allowed us to imitate what the conditions are like on the moon with the resources we had. The next constant variable is the humidity of the air encroaching the plants. If there is too much humidity, mold and bacteria will be given a good place to grow. If there is too little humidity, then the plants will have a lot of trouble removing carbon from the atmosphere.

Pot ID	Site Location Code	Mix Proportion (Soil to Regolith)	Average Room Temp	Measure of water added	Frequency of water addition	Average Soil PH	Average Moisture Measurement	Average Room Humidity	Quantity of fertilizer used (g)
1	RR	50-50	68.5	30 ml	Daily	6.95	3.54	26.91	0.25
2	PR	50-50	70	30 ml	Alternate days	7.50	3.00	28.46	0.25
3	KS	50-50	67	30 ml	Twice a day	7.13	3.00	27.46	0.25
4	RR	37.5 - 62.5	68.5	30 ml	Daily	6.96	3.68	26.83	0.25
5	PR	37.5 - 62.5	70	30 ml	Alternate days	7.50	3.00	28.50	0.25
6	KS	37.5 - 62.5	67	30 ml	Twice a day	7.25	3.00	27.46	0.25
7	RR	25-75	68.5	30 ml	Daily	6.98	3.93	26.83	0.25
8	PR	25-75	70	30 ml	Alternate days	7.25	3.00	28.58	0.25
9	KS	25-75	67	30 ml	Twice a day	7.13	3.00	27.46	0.375
10	RR	100-0	68.5	30 ml	Daily	6.91	5.43	26.83	0.25
11	PR	100-0	70	30 ml	Alternate days	7.00	4.71	28.50	0.25
12	KS	100-0	67	30 ml	Twice a day	7.00	4.00	27.46	0.125

Table 3: Experimental conditions utilized for growth garden cress

Average pH across site locations and pots were in the range of 6.9 to 7.5. The addition of ammonium sulfate 7 did not alter the pH across sites and pots.

Results

Over the growth cycle, the influence of the parameters on the growth of garden across the 12 pots in 3 site locations are presented in Table 4 and Figure 1. Mean and standard deviation of plant height is presented in Table 5. The results of one-way ANOVA show an overall significant difference between the four types of regolith-soil mixes with regard to plant height (Table 5 ;F= 13.43 ; df= 3 ; p<.05). The results of post hoc Bonferroni show significant plant height difference between pots with zero regolith and all three pots with regolith mixed along with the soil (Table

5). Though the mean yield on the 75% regolith mix pot was the lowest at 2.3, but there was no significant difference in yield between the pots with 50%, 62.5% or 75% regolith mixture.

Pot ID	Site Location Code	Mix Proportion (Soil to Regolith)	Plant final height (cm)	Plant Final Weight (g)
1	RR	50-50	2.0	17
2	PR	50-50	2.0	5
3	KS	50-50	3.2	5
4	RR	37.5 - 62.5	2.2	6
5	PR	37.5 - 62.5	1.5	2
6	KS	37.5 - 62.5	3.8	5
7	RR	25-75	1.6	8
8	PR	25-75	1.8	1
9	KS	25-75	3.5	5
10	RR	100-0	7.2	24
11	PR	100-0	8.9	8
12	KS	100-0	5.8	10

Table 4: Plant yield at harvest after 29 lunar days

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
100% soil	3	7.300	1.5524	.8963	3.444	11.156	5.8	8.9
25% Soil	3	2.300	1.0440	.6028	-.294	4.894	1.6	3.5
37.5% Soil	3	2.500	1.1790	.6807	-.429	5.429	1.5	3.8
50% Soil	3	2.400	.6928	.4000	.679	4.121	2.0	3.2
Total	12	3.625	2.4275	.7008	2.083	5.167	1.5	8.9

Table 5: Descriptive Statistics of plant height

Figure 1: Pots 2, 5, 8 and 11 on day 14

ANOVA

Plant final height (cm)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	54.082	3	18.027	13.428	.002
Within Groups	10.740	8	1.343		
Total	64.822	11			

Table 5: Analysis of variance of plant height

Multiple Comparisons

Dependent Variable: Plant final height (cm)

	(I) Mix Proportion	(J) Mix Proportion	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Bonferroni	100% soil	2	5.0000*	.9460	.004	1.709	8.291
		3	4.8000*	.9460	.006	1.509	8.091
		4	4.9000*	.9460	.005	1.609	8.191
	25% Soil	1	-5.0000*	.9460	.004	-8.291	-1.709
		3	-.2000	.9460	1.000	-3.491	3.091
		4	-.1000	.9460	1.000	-3.391	3.191

37.5% Soil	1	-4.8000*	.9460	.006	-8.091	-1.509
	2	.2000	.9460	1.000	-3.091	3.491
	4	.1000	.9460	1.000	-3.191	3.391
50% Soil	1	-4.9000*	.9460	.005	-8.191	-1.609
	2	.1000	.9460	1.000	-3.191	3.391
	3	-.1000	.9460	1.000	-3.391	3.191

*. The mean difference is significant at the 0.05 level.

Table 6: Comparison of plant yield mean difference across mix proportions

As mentioned in the hypothesis, the purpose of this analysis is to examine whether the experimental variables predict plant yield, both in terms of plant height and harvested plant weight. A linear regression was conducted to estimate the linear equation that predicts levels of plant yield among the pots with varying the regolith-soil mixes. Prior to conducting the analysis, several descriptive statistics and graphs were generated.

A Pearson correlation coefficient and a scatter plot show a significant linear relationship between the variables of interest and plant yield. The results of the multiple regression analysis revealed that three of the six factors emerged as significant predicators of plant height ($F = 23.04$; $p < 0.05$). Average moisture in the soil, total light hours and light level (lumens) were the strongest predictors of plant height. Multicollinearity was not found to exist. Similar regression analysis for predicting plant weight did not yield any significant results.

	Plant Height		Standardized Coefficients			Collinearity Statistics	
Model	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	-7.475	17.258		-.433	.683		
Percentage Regolith	.012	.020	.152	.637	.552	.122	8.206
Light level(lumens)	.016	.004	.633	4.238	**.008**	.313	3.199
Total Light Hours	.010	.002	.767	4.117	**.009**	.201	4.971
Average Soil pH	-1.190	2.250	-.101	-.529	.620	.191	5.229
Average Moisture Measurement	2.599	.742	.855	3.504	**.017**	.117	8.536

Interaction – Light X % Regolith	-7.156E-5	.000	-.445	-1.711	.148	.103	9.709
$p < 0.05$							

Table 7: Results of regression analysis

Conclusion

The results of this study indicate that the key parameters that enhance plant (Cress) yield are average moisture content, total duration and intensity of light during the growth cycle. Since the intensity and duration of light is a critical parameter that affects plant growth, matching the growth cycles with lunar day can ensure high plant yield. Moreover, the growth of Cress did not vary significantly based on variations in the composition of soil to regolith. This implies that significant plant yield can be achieved even with very high levels of regolith. Indeed, this is not very surprising in light of the currently accepted hypothesis on the origins of moon. The 'Giant Impact Hypothesis' suggest that the moon was formed from debris ejected by a large off-center collision of the proto-Earth with a mars sized planetesimal. The composition of regolith is expected to be similar to that of soil providing the possibility for supporting plant growth. This study has not considered the effect of gravity or the atmospheric conditions of the moon. These will have a profound on plant yield. The reuse of regolith-soil mix over multiple growth cycles should also be investigated.

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