Developing a Model In-Situ Resource Utilization System for Oxygen Sustaining Life Support and Launch Cost Reduction for Mars

All photographs/charts/graphs were created by Finalist Ariella Blackman (2021) unless otherwise noted

Introduction

Life support systems (LSS) for Mars exploration

Too expensive to launch materials from Earth to Mars

In-Situ Resource Utilization (ISRU)
- ISRU: the use of local resources (on Mars) to support human activity

Reduces launch mass and therefore cost

Water | Food | Atmosphere | Protection

Martian ISRU:
- Subsurface water ice
- Martian regolith
- Atmospheric gases

Atmospheric Composition	
Atmospheric Constituent	Composition (%)
Carbon dioxide (CO_2)	94.9 (±1.6)
Nitrogen (N_2)	2.79 (±0.05)
Argon (Ar)	2.08 (±0.02)
Oxygen (O_2)	0.174 (±0.006)
Carbon monoxide (CO)	0.0747 (±0.00026)

Table created by Lotto et al. (2018)

Lotto, M. A., Klaus, D. M., & Hynek, B. M. (2018). *Atmospheric composition* [Table]. Mary Ann Liebert, Inc. https://doi.org/10.1089/space.2018.0019

ISRU is mission enabling and can be used to convert CO_2 in the Martian atmosphere into O_2 for LSS

- Many current ISRU O_2 production methods are mechanical
- Plants convert CO_2 to O_2 and are multifunctional
  - Can minimize launch mass and cost

Earth soil to Mars = too expensive → ISRU to grow in Martian regolith

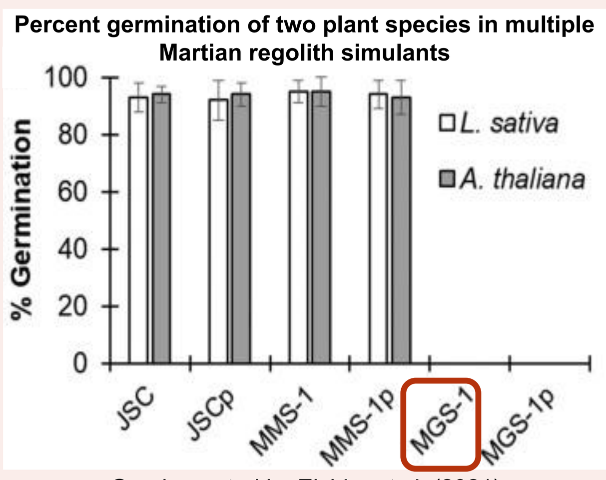
Review of Literature

Mars Global Simulant (MGS-1)

- Most accurate Martian regolith simulant to date
- Curiosity Rover data used
- Assembled from individual components

Sample of MGS-1
Photograph by Cannon et al. (2019)

Plant growth in regolith simulants



Graph created by Eichler et al. (2021)

Unable to germinate in MGS-1 → Issues in real Martian regolith

Growth in substrate ratios

- Plants in ratios of Earth soil and MMS
  - Less accurate simulant
  - Did not study O_2 production

Kale plants grown in Earth soil and mixtures containing Martian regolith simulant
Photograph created by Fitchett et al. (2020)

Gap in Knowledge

Do ratios of MGS-1 and Earth soil support plants?

What is the ideal ratio for ISRU benefits?

How many plants are necessary to support life per person per day?

Hypothesis

A threshold exists where tepary beans *(Phaseolus acutifolius)* will be capable of growing and producing O_2 in a mixture of MGS-1 and Earth soil, as measured by biomass produced.

Goal

Determine an ideal substrate ratio to model a sustainable, plant-based, O_2 production LSS that uses ISRU of Martian regolith.

Ideal substrate ratio

Sufficient oxygen production | Minimal Earth soil/launch mass

Methodology

Variables

MGS-1

- Most accurate representation of Martian regolith to date

Sample of MGS-1

Potting Mix

- Counteracts challenges of MGS-1
  - Contains perlite (water retention)
  - High in ammonium nitrate (.21%)

Potting mix sample
Photograph taken by The Scotts Company LLC. (2021)

Tepary Beans *(Phaseolus acutifolius)*

- Resilient for Mars environment
  - Harsh environment
  - Low water

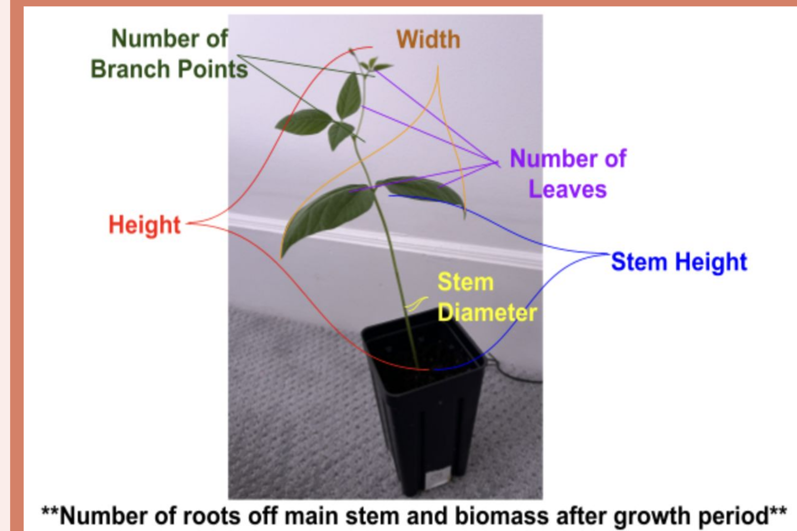
Tepary bean plant
Photograph taken by Native Seeds Search (2021)

Independent Variable:

Percent of MGS-1 in MGS-1 and potting mix substrate (percent by volume)

Samples of substrates used in study

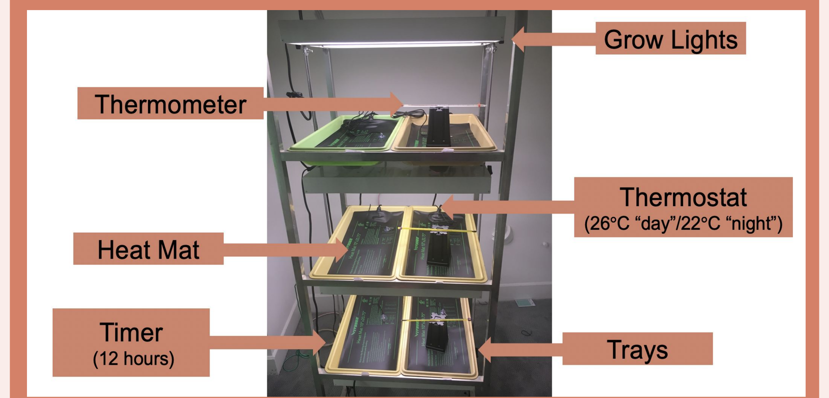
Dependent Variables:



Daily measured growth parameters labeled on tepary bean plant

Controlled Variables:

- Controlled environment in home basement important for O_2 calculations
  - Simulated day/night, measured 2x/day
  - Rotated tray to mitigate heat gradient impacts



Environmental controls labeled on study set-up

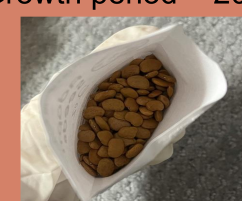
Procedures

Treating Substrates

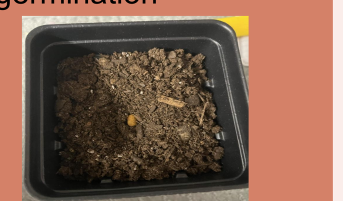
MGS-1 aggregates when watered → inhibits root growth

Growing Plants

- 560 cm^3 substrate, 3.5" x 3.5" x 5" container
  - Room for roots
- Planted 2 cm deep, one bean per container
- Growth parameters measured daily
- Growth period = 20 days post-germination



Container of tepary beans



Tepary beans during planting

Measuring Biomass

Isolate plant → Wet total biomass → Dehydrate in drying oven → Above and below-ground dry biomass → Cut stem/roots → Dry total biomass

Results & Discussion

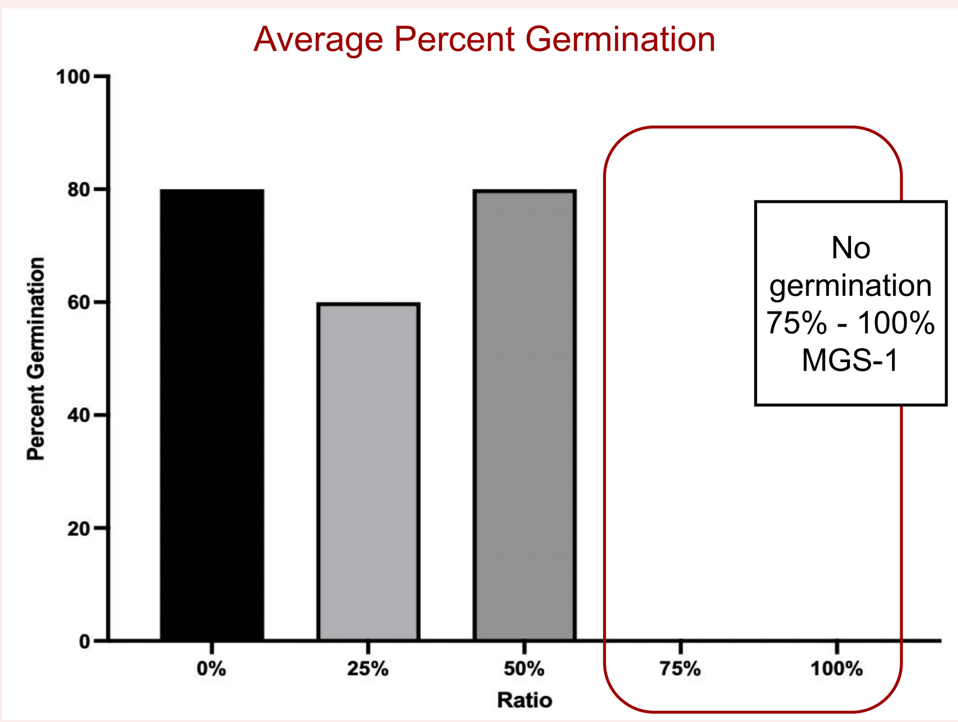


Figure 1: Percent germination of plants grown in multiple substrate ratios, Z-test for proportions indicated no significant difference between germination in 0%, 25%, and 50% MGS-1 (p>.05).

Growth threshold exists between 50% and 75% MGS-1

More below ground biomass suggests that 50% MGS-1 allocated more resources towards obtaining water

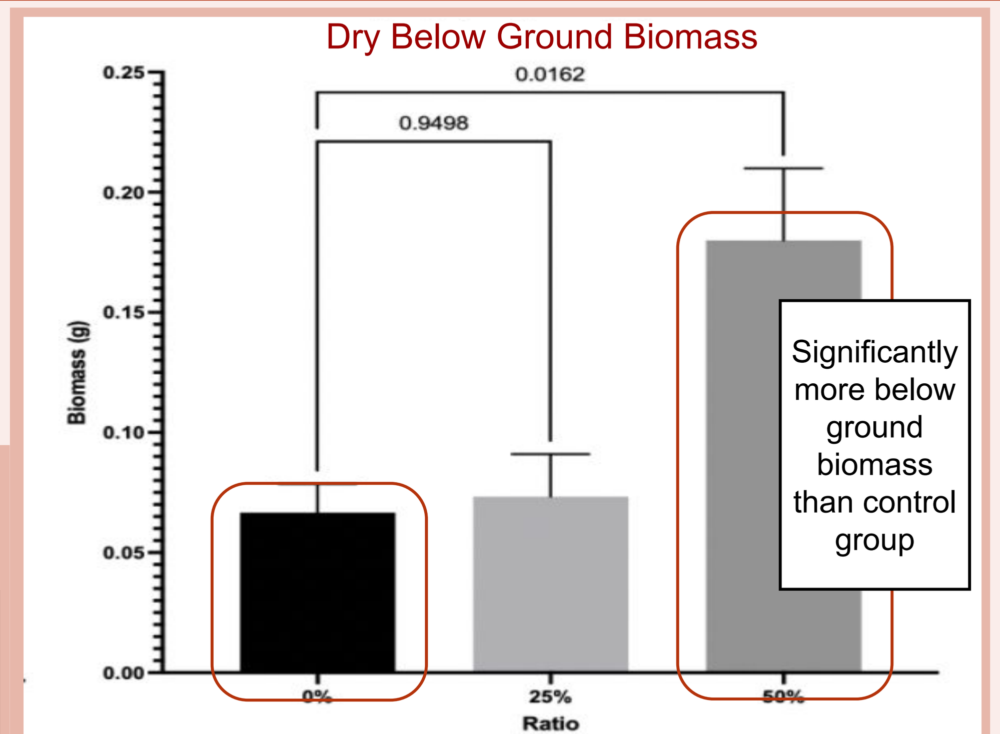


Figure 2: Mean dry below ground biomass of plants grown in different substrate ratios, error bars = SEM, one-way ANOVA supports a significant effect of substrate ratio (F=10.05, df=7, p=0.0177), Tukey's HSD Test for multiple comparisons supports that the mean values of dry below ground biomass were significantly different between 50% MGS-1 and control (p<.05).

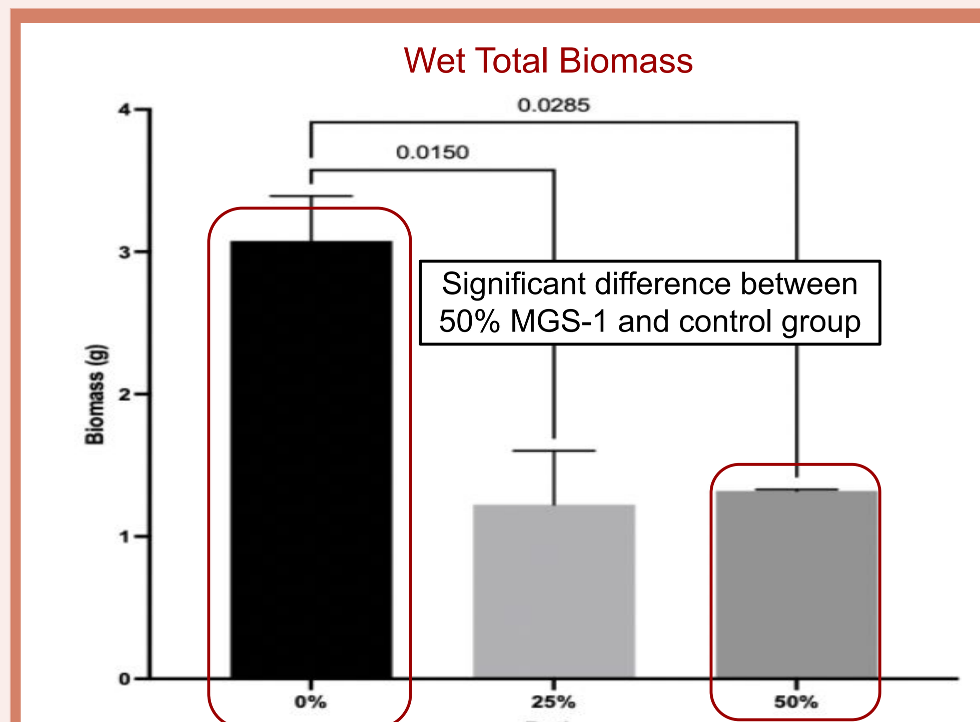


Figure 3: Mean wet total biomass of plants grown in different substrate ratios, error bars = SEM, one-way ANOVA supports a significant effect of substrate ratio (F=10.60, df=7, p=0.0159), Tukey's HSD Test for multiple comparisons supports that the mean values of wet total biomass were significantly different between 25% MGS-1 and control, and 50% MGS-1 and control (p<.05).

Difference between wet biomasses but not dry biomasses suggests plant water uptake impacted plant growth in MGS-1

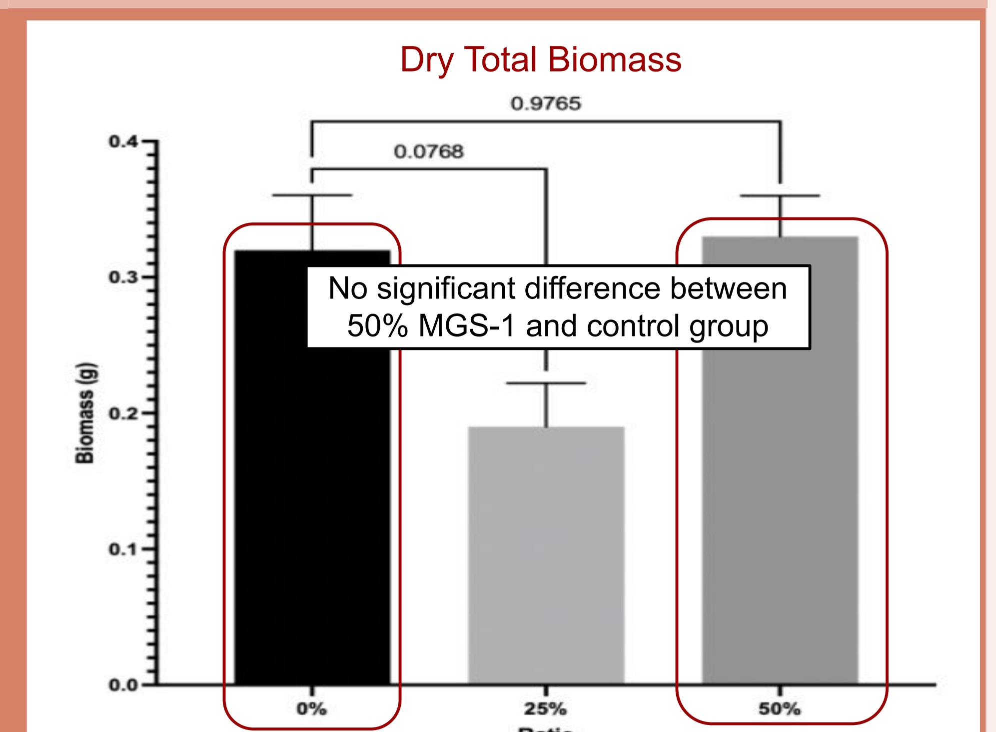


Figure 4: Mean dry total biomass of plants grown in different substrate ratios, error bars = SEM, one-way ANOVA does not support a significant effect of substrate ratio (F=4.745, df=7, p=0.0699).

Conclusions:
Water retention properties of MGS-1 affected plant growth
If MGS-1 can be treated to retain water more similarly to Earth soil, plants may be able to grow in larger quantities of MGS-1

Application

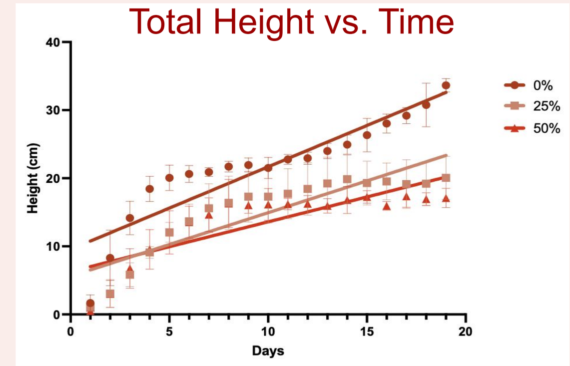


Figure 5: Linear regression of plant height vs. time, error bars = SEM.

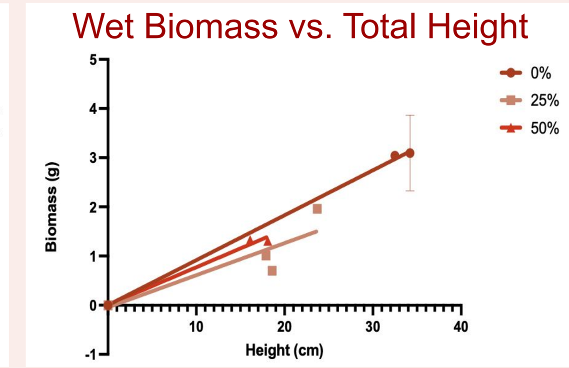


Figure 6: Linear regression of wet biomass vs. height, error bars=SEM, ANOVA does not support a significant effect of substrate ratio (F=1.540, df=12, p=.2613).

Extrapolate plant height at 75 days (estimated plant maturity)

Biomass at 75 days: linear relationship between biomass and height

Crop	Biomass Carbon Fraction, BCF
Dry Bean	0.45
Lettuce	0.40
Peanut	0.50
Rice	0.44
Soybean	0.46

Table created by Anderson et al. (2018)

Anderson, M. S., Ewert, M. K., & Keener, J. F. (2018). *Biomass carbon and oxygen production fractions for nominal temperature regime and photoperiod* [Chart]NASA.https://ntrs.nasa.gov/api/citations/20180001338/downloads/ 20180001338.pdf

$$6CO_2 + 6H_2O \rightarrow \mathbf{C_6H_{12}O_6 + 6O_2}$$

$$1\ mol\ C = 1\ mol\ O_2$$

Assumption based on photosynthesis equation

Calculate carbon content per plant using BCF (45% dry biomass carbon)

Photosynthesis: C and O_2 produced in 1:1 ratio, calculate O_2 per plant

Case	O2 Consumption (kg)
5th Percentile	0.62
50th Percentile	0.86
95th Percentile	1.13
Reference CM	0.92

Oxygen consumption per day for crew members based on mass percentile
Table created by Anderson et al. (2018)

Anderson, M. S., Ewert, M. K., & Keener, J. F. (2018). *Daily total metabolic output for all crewmembers* [Chart]. NASA. https://ntrs.nasa.gov/api/citations/20180001338/downloads/20180001338.pdf

$$y = \frac{0.92\ kg\ O_2}{kg\ O_2\ per\ plant}$$

Number of Plants for 0%

$$y = \frac{0.92}{0.00106}$$

$$\boxed{y = 867\ plants}$$

Number of Plants for 25%

$$y = \frac{0.92}{0.000918}$$

$$\boxed{y = 1003\ plants}$$

Number of Plants for 50%

$$y = \frac{0.92}{0.00152}$$

$$\boxed{y = 606\ plants}$$

Estimate number of plants to support life per person per day in each substrate (assume O_2 consumption of .92 kg per person per day)

Less efficient O_2 production

Mass of Soil for 0%

$$0.207 = \frac{m}{(560)(867)}$$

867 plants → 101,000g

Mass of Soil for 25%

$$0.207 = \frac{m}{(420)(1003)}$$

1003 plants → 87,200g

Mass of Soil for 50%

$$0.207 = \frac{m}{(280)(606)}$$

606 plants → 35,100g

Earth-based soil mass decreases

Estimate total amount of potting soil necessary to grow enough plants to support life in each substrate ratio

Conclusion:
Ideal substrate ratio is maximum MGS-1 without inhibiting germination
Therefore, ideal ratio is near growth threshold of 50% - 75% MGS-1

Limitations

O_2 and mass values are first order estimates

Biomass carbon fraction used generic "dry bean" and Earth conditions

Different above/below ground biomass ratios; model uses total biomass

Values calculated in model may not be exact, but trends and therefore ideal ratios likely hold true

Future Research

Model accuracy

Controlled environment: directly measure gas exchange

Substrates between 50% and 75% MGS-1 to define threshold

Examine impacts of nitrogen fixation in legumes

LSS design

Grow pioneer species in MGS-1 to fertilize with organic matter

Other mission costs impacted by growth substrate

Conclusion

- Hypothesis supported
  - Growth threshold exists between 50% and 75% MGS-1
- Benefits of decreasing Earth soil in the substrate outweigh issues of decreased O_2 production with more MGS-1
  - Ideal ratio is near growth threshold
- Plants could be a viable ISRU life support system for O_2 production that reduces launch mass and therefore cost of a human Mars mission