

Plant the Moon Challenge: Spring 2026

FINAL REPORT

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TITLE

“Evaluation of Banana Peel Nano-Fertilizer for Food Crops in Lunar Regolith Simulant during Post-germination Growth and Substrate Nutrient Analysis.”

■ Introduction

As space exploration becomes more advanced, scientists have begun exploring how plants could be grown beyond Earth. This is especially important for places like the Moon, where future missions may rely on being able to grow crops with their given conditions. The surface of the moon is covered in a substance called regolith, which is very different from Earth's soil. Regular soil contains organic matter and microorganisms that help support plant growth, but regolith does not, making it a much more difficult environment for plants to survive in.

Due to regolith lacking biological components, it also has physical properties that can make plant growth more challenging. Its particles are very fine and irregular, which allows them to pack closely together. This can limit the ability of a plant's roots to spread and take in water. At the same time, the way regolith holds water is different from soil, which can create inconsistent growing conditions. Plants grown in regolith often do not grow as well as those in normal soil as a result.

The way various fertilizers interact under low nutrient conditions is another crucial aspect of plant growth research. Plants may rely on organic matter and naturally occurring nutrients in ordinary soil systems, but in harsher or artificial environments, external nutrient

sources become far more crucial. As a result of this, when regular soil conditions are unavailable, researchers frequently investigate alternate fertilizers to evaluate how well they can promote plant health. Gaining insight into how plants react to these types of details can help develop better methods for producing food in settings where conventional agriculture is not possible.

■ Theory

Plant growth depends on having access to key nutrients, especially nitrogen, phosphorus, and potassium. These nutrients support basic functions like leaf development, energy transfer, and overall growth. In normal soil, plants are able to get these nutrients through organic matter and natural processes that happen over time. When those processes are missing, plants have to rely much more on whatever nutrients are added from the outside.

This becomes more noticeable in something like lunar regolith simulant. Since it does not contain organic matter or living organisms, it does not naturally support nutrient cycling the way soil does. Even if some elements are present, they are not always in forms that plants can easily use. As a result, plants growing in this type of environment are more likely to experience stress and slower growth. Studies have shown that while plants can survive in regolith, they often do not develop as well as they do in regular soil (Paul et al., 2022).

Fertilizer plays a much bigger role when the growing environment is limited like this. Nutrients such as nitrogen help with leaf and stem growth, phosphorus is important for root development, and potassium helps regulate water and overall plant health. When these are added in the right amounts, they can improve how well a plant grows. Still, it is not just about how much nutrient is added, but how available it is to the plant.

The banana peel nano fertilizer used in this study is based on that idea. Banana peels contain nutrients, especially potassium, and when they are processed into much smaller particles, those nutrients may be easier for plants to absorb. Smaller particles can move more easily through the root system, which may allow plants to take in nutrients more efficiently compared to a standard fertilizer. This is one reason why nano fertilizers are being looked at more closely in plant growth research (Hussein et al., 2019).

The type of plant also matters. Tomato plants usually grow faster and require more nutrients, especially nitrogen, to support that growth. Basil tends to grow at a slower rate and may respond differently when nutrient levels change. For that reason, the two plants may not show the same results even when they are grown under the same conditions.

The growing environment also changes how effective a fertilizer can be. Soil is generally better at holding water and nutrients, which helps plants absorb what they need over time. Regolith simulant does not have those same properties, so nutrients may not stay available for as long. Even with that limitation, a fertilizer that improves nutrient uptake could still make a difference in how well plants grow.

Based on this, it is expected that plants grown in soil will perform better overall than those grown in regolith simulant. It is also expected that the banana peel nano fertilizer will lead to better growth compared to the regular fertilizer, since the nutrients may be easier for the plants to absorb. Tomato plants are likely to show a stronger response to these changes than basil since they generally require more nutrients to support their growth.

To evaluate this, plant growth can be observed through changes in height, spread, and leaf development. Looking at these factors makes it easier to compare how each plant responds under different conditions and gives a clearer picture of how both the environment and the fertilizer affect growth.

■ Hypotheses

Our project investigates the growth of tomato and basil plants by comparing experimental groups treated with Banana Peel Nano Fertilizer (BPNF) to control groups without fertilizer, using both regular soil and lunar regolith simulant. If plants are grown with BPNF, then they will exhibit higher concentrations of essential nutrients—specifically nitrogen, potassium, and phosphorus—than the plants grown without the nano fertilizer.

We expect that our plants grown in regular soil will generally show stronger growth due to its natural nutrient content and water retention properties. In contrast, lunar regolith simulant lacks organic matter, has low nutrient availability, and exhibits poor water retention, which limits nutrient diffusion and root support. However, the addition of BPNF is predicted to significantly improve plant growth in the regolith simulant. In other words, the BNF features will fill in for the factors that the lunar regolith lacks.

This is because BPNF enhances diffusion and fluid transport by increasing surface area at the nanoscale, improving water distribution, and helping retain nutrients near plant roots. As a result, the combination of regolith simulant and BPNF may compensate for the soil's physical and chemical limitations, leading to improved nutrient uptake and overall plant development. The nano fertilizer will provide a greater surface area for nutrients having to be absorbed for the plants and their roots. We are examining this process with the mindset of tomato and basil plants in specific conditions different from regular soil to prosper in shoot growth and root nutrition.

The addition of Banana Peel Nano Fertilizer (BPNF) will improve fluid and nutrient transport within plant roots. Because lunar regolith environments simulate lower gravity conditions, water and nutrient movement is less efficient compared to Earth soil. The use of nanoparticles enhances this process by increasing surface area and improving the dissolution and diffusion of essential nutrients. As a result, nutrients can move more efficiently through the soil and into the plant roots, supporting better growth despite reduced gravitational effects.

- H1: Tomato and basil plants grown in lunar regolith simulant with Banana Peel Nano Fertilizer will exhibit increased shoot growth compared to plants grown in regolith without fertilizer.
- H01: The addition of Banana Peel Nano Fertilizer to lunar regolith simulant will not significantly affect the plant's shoot increase in tomato and basil plants.
- H2: Banana Peel Nano Fertilizer will enhance diffusion and fluid transport in the soil, resulting in higher concentrations of nitrogen, potassium, and phosphorus in the roots of tomato and basil plants.
- H01: Banana Peel Nano Fertilizer will not significantly affect diffusion, fluid transport, or the concentration of nitrogen, potassium, and phosphorus compared to plants grown without fertilizer or in regular soil.

■ **Measurement and Methods**

Experimental Design

This study investigates whether the Banana Peel Nano Fertilizer (BNF), which has been shown to increase germination percentage, can promote post-germination growth in food crops such as tomato and basil. Two substrates were used: soil and lunar regolith simulant. Two fertilizer treatments were applied: regular fertilizer (RF) and BNF. RF was a customized fertilizer prepared with the same concentrations of nitrogen, potassium, and phosphorus as BNF, dissolved in laboratory-prepared reverse osmosis water. Each plant was grown in a

separate container with a total of 28 plants across 8 treatment groups arranged in a factorial design. To focus on the post-germination process, germination was conducted outside the substrates prior to transplanting, as seeds have been confirmed to germinate in lunar regolith within two days(NASA, 2025).

Substrate	Fertilizer	Crop	n
Soil	RF	Tomato	4
		Basil	4
	BNF	Tomato	4
		Basil	4
Regolith	RF	Tomato	3
		Basil	3
	BNF	Tomato	3
		Basil	3
Total			28

Variables

- **Independent Variables**

The independent variables were substrate type (soil and lunar regolith simulant) and fertilizer type (RF and BNF).

- **Dependent Variables**

The dependent variables measured were shoot length (cm), canopy width (cm), and leaf count.

- **Controlled Variables**

The following variables were kept constant throughout the experiment: volume of fertilizer applied, light conditions, temperature, container size, and plant species (tomato and basil).

Equipment

- NPK Nutrients Test Kit
- Ruler
- Scale
- High-speed blender,
- heating apparatus

- vacuum filter.
- Spectrophotometer

Growth Condition

Figure 1. An automated irrigation system was set to operate twice daily at 7:30 AM and 8:30 PM for 10 minutes per cycle. The irrigation water, containing either RF or BNF at the designated concentrations, circulated through the system and was delivered to each plant from the bottom of the container.

Figure 2. An automated red and blue grow lighting system was set to operate on a 12-hour cycle(7:00 AM-7:00 PM on, 7:00 PM -7:00 AM off), providing supplemental light in addition to natural sunlight.



Figure 1. Irrigation system (Watering cycle: 7:30 AM and 8:30 PM)



Figure 2. Lighting system (7:00 AM-7:00 PM on, 7:00 PM -7:00 AM off)



Figure 3. Complete experimental setup

Experimental Procedure

1. Plant preparation

Seeds were wrapped in a moist paper towel, sealed in a ziplock bag, and left to sprout. Sprouted seeds were transplanted into the prepared containers after one week.

2. Substrate preparation

Each container was lined with a coffee filter to retain moisture and prevent rapid leaching. A cotton wick was inserted at the base of each container to maintain consistent moisture distribution throughout the substrate through capillary water movement.

3. Fertilizer Preparation

NPK fertilizer

NPK refers to macronutrients most demanded by plants: nitrogen (N), phosphorus (P), and potassium (K). These nutrients are frequently deficient in natural soil, making NPK fertilization one of the most common approaches to improving plant growth. Unlike potassium, which can be released through mineral weathering, nitrogen and phosphorus are not replenished through atmospheric reactions and must therefore be absorbed by plants through the roots. Supplementing these nutrients supports plant metabolism and creates conditions conducive to accelerated growth.

RF (Regular Fertilizer)

The RF used in this study was a customized laboratory-prepared NPK blended fertilizer, formulated by dissolving nitrogen, phosphorus, and potassium at equivalent concentrations to BNF, dissolved in reverse osmosis water.

	Concentration [ppm]	reverse osmosis water[L]
Nitrogen[N]	19	3
Potassium[K]	1.5	
Phosphorus[P]	3.5	

BNF (Banana Peel Nano Fertilizer)

BNF leverages nanotechnology and green chemistry to extract nanoscale(19-55nm) NPK elements from banana peel waste. Banana peels account for approximately 18-33% of the total fruit mass and are widely discarded as solid waste (Hussein et al., 2019). Using BNF is an environmentally sustainable alternative to conventional fertilizers. BNF was prepared in the laboratory following the protocol described by Hussein et al. (2019).

Fertilizer Application Schedule

Fertilizer was applied weekly from week one to four at a consistent dosage; RF: 45ml and BNF 4.83g. As RF and BNF differ in forms, powder and liquid, the amounts applied varied; however, the concentrations were calculated to be equivalent between the two treatments.

week	Total Amount of RF[ml]	Total Amount of BNF[g] ¹
1	45	4.83
2	90	9.67
3	135	14.50
4	180	19.34

¹BNF was dissolved in 1 L of reverse osmosis water prior to application.

4. Measurements

Shoot length was measured weekly for five weeks, starting in the first week after fertilizer application. Canopy width and leaf count were additionally recorded in the final week. Substrate NPK Nutrient concentrations were determined spectrophotometrically at the end of the experiment.

Substrate Nutrient Analysis (NPK Determination)

The concentrations of nitrogen (N), phosphorus (P), and potassium (K) in the experimental substrates (Regolith Banana Fertilizer, Soil Banana Fertilizer, Regolith Regular Fertilizer and Soil Regular Fertilizer) were quantified via UV–Vis spectrophotometry using a Thermo Fisher Spectronic 200 in combination with the LaMotte NPK Test Kit. This analysis was designed to evaluate the relative nutrient availability and retention capacity of each substrate under identical experimental conditions.

Calibration and Standard Preparation

Calibration curves were established for each analyte prior to sample analysis. Stock solutions (2000 ppm) were prepared using analytical-grade ammonium nitrate (NH_4NO_3) and monobasic potassium phosphate (KH_2PO_4), providing known concentrations of nitrate (NO_3^-), potassium (K^+), and phosphate (PO_4^{3-}).

Serial dilutions of the stock solutions were performed to generate a set of working standards spanning the expected concentration range of the samples. Absorbance measurements of these standards were used to construct calibration curves for each nutrient. Linear regression analysis was applied to determine the relationship between absorbance and concentration, ensuring correlation coefficients (R^2) ≥ 0.99 for all analytes.

Spectrophotometric Determination

Absorbance measurements were conducted following the colorimetric protocols specified in the LaMotte test kit. The relationship between absorbance and concentration was interpreted according to the Beer–Lambert law:

$$A = \epsilon b c$$

where A is the measured absorbance, ϵ is the molar absorptivity, b is the optical path length of the cuvette (typically 1 cm), and c is the analyte concentration. Calibration curves were used to convert absorbance values into concentrations expressed in ppm.

Sample Extraction and Analysis

Substrate samples were processed according to the standardized extraction procedures provided by the LaMotte NPK Test Kit. Extracted solutions were filtered as required to remove particulates prior to analysis.

Absorbance readings were obtained using the Spectronic 200 spectrophotometer at the appropriate wavelengths for each analyte, as defined by the colorimetric method. Blank corrections were applied using reagent controls to minimize background interference.

	Wavelength [nm]
Nitrogen[N]	515
Potassium[K]	770
Phosphorus[P]	880

Quality Control and Data Reliability

To ensure analytical accuracy and precision, the following quality control measures were implemented:

- Calibration verification using independent standards
- Blank subtraction to correct for reagent and solvent absorbance
- Monitoring of instrument stability and baseline drift

The resulting nutrient concentrations represent estimates of bioavailable N, P, and K in each substrate. These data were used to assess differences in nutrient retention and release behavior between Regolith Banana Fertilizer, Soil Banana Fertilizer, Regolith Regular Fertilizer and Soil Regular Fertilizer, providing insight into their suitability for plant growth applications.



Spectronix 200 Thermofisher

5. Statistical Analysis

Statistical significance of shoot length, canopy width, and leaf count was assessed using one-way ANOVA followed by Tukey's HSD post-hoc test, performed in R (version 4.5.3).

■ Analysis and Results

Data Analysis

Significance testing (ANOVA followed by Tukey's HSD post-hoc test)

Statistical Analysis

For shoot length, consistent results were observed in both tomato and basil, with the largest average mean difference occurred between Soil (BNF) and Regolith (RF).

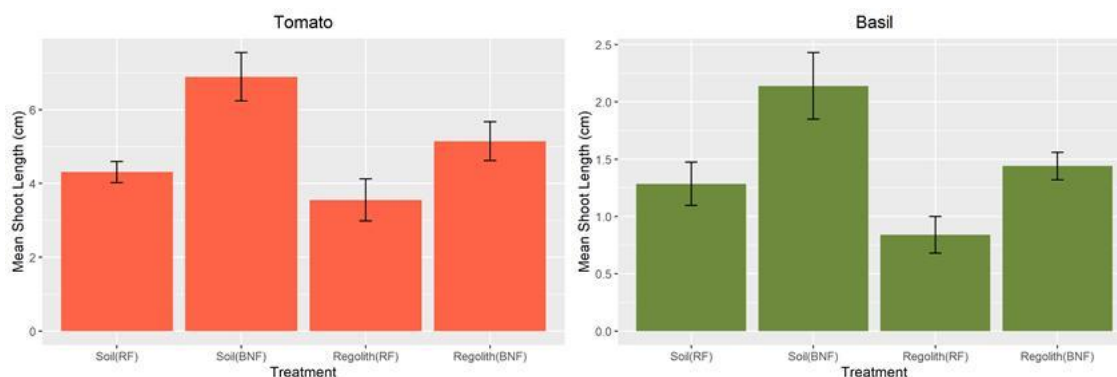
For canopy width, the largest mean difference in basil also occurred between Soil (BNF) and Regolith (RF), while in tomato, the largest difference was observed between Soil (RF) and Soil (BNF). A similar pattern was found in leaf count for both species, with the largest mean difference occurring between Soil (RF) and Soil (BNF). This observation suggests that Soil (BNF) is the most efficient growth-accelerator pair across all measured parameters. This is further supported by the statistical significance of the comparisons involving Soil(BNF), which consistently yielded the lowest p-values, indicating that the superior performance of Soil(BNF) was unlikely to be due to chance.

Meanwhile, Soil (RF) and Regolith (RF) showed the lowest mean growth values across most parameters, indicating that laboratory prepared NPK is less effective at promoting nutrient uptake. This indicates BNF performs more efficient replenishment in roots.

Overall, tomato demonstrated substantially greater growth than basil across all measured parameters. In addition to higher absolute values, the tomato presented smaller standard errors, which indicates that the tomato has a more reliable, consistent growth pattern than basil throughout the experiment. It is determined that tomato is more compatible with BNF than Basil.

Across all results, Regolith (BNF) consistently outperformed Regolith (RF), demonstrating that even nutrient-poor regolith retains the potential for plant growth when supplemented with BNF.

Shoot length



Tomato Shoot Length

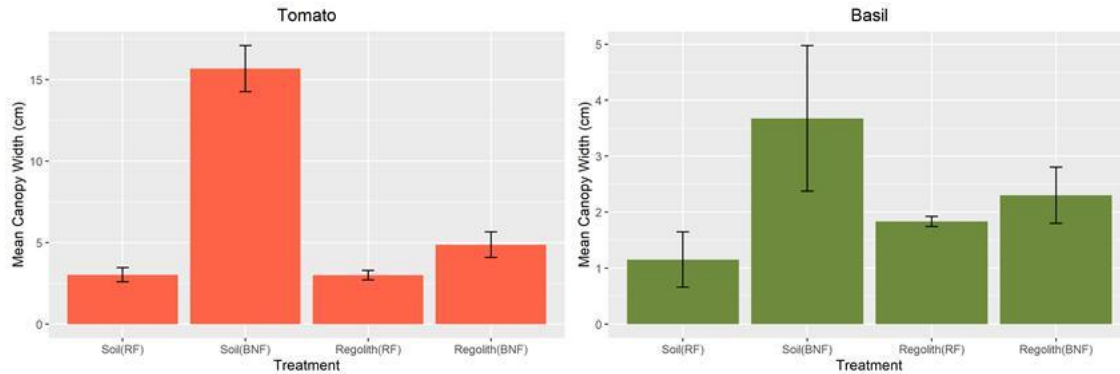
Comparison	diff	lwr	upr	p adj	Significance
regolith_RF – regolith_BNF	-1.5933333	-3.7127394	0.5260727	0.2053923	marginally significant
soil_BNF – regolith_BNF	1.7458333	-0.2366895	3.7283562	0.1035938	marginally significant
soil_RF – regolith_BNF	-0.8366667	-2.8191895	1.1458562	0.6832794	n.s.
soil_BNF – regolith_RF	3.3391667	1.3566438	5.3216895	0.0002022	significant
soil_RF – regolith_RF	0.7566667	-1.2258562	2.7391895	0.7464799	n.s.
soil_RF – soil_BNF	-2.5825000	-4.4179595	-0.7470405	0.0023728	significant

Basil Shoot Length

Comparison	diff	lwr	upr	p adj	Significance
regolith_RF – regolith_BNF	-0.6000000	-1.4710756	0.2710756	0.2753268	marginally significant
soil_BNF – regolith_BNF	0.7	-0.1148166	1.5148166	0.1170313	marginally significant
soil_RF – regolith_BNF	-0.1550000	-0.9698166	0.6598166	0.958464	n.s.
soil_BNF – regolith_RF	1.3	0.4851834	2.1148166	0.0004574	significant
soil_RF – regolith_RF	0.445	-0.3698166	1.2598166	0.4796933	n.s.

soil_RF –					
soil_BNF	–0.8550000	–1.6093736	–0.1006264	0.0201231	significant

Canopy Width



Tomato Canopy

Width

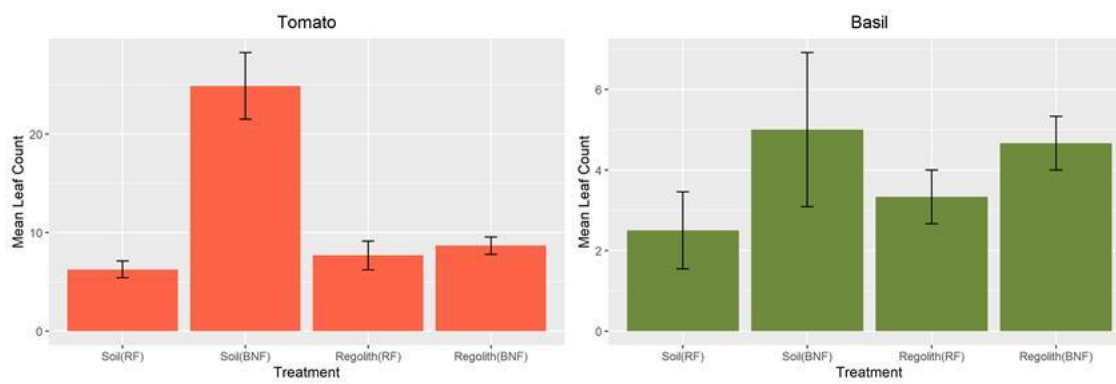
Comparison	diff	lwr	upr	p adj	Significance
regolith_RF – regolith_BNF	–1.8666667	–6.2163820	2.4830486	0.5758299	n.s.
soil_BNF – regolith_BNF	10.8083333	6.7395474	14.8771193	0.0000507	significant
soil_RF – regolith_BNF	–1.8416667	–5.9104526	2.2271193	0.5353131	n.s.
soil_BNF – regolith_RF	12.675	8.6062141	16.7437859	0.0000123	significant
soil_RF – regolith_RF	0.025	–4.0437859	4.0937859	0.9999974	n.s.
soil_RF – soil_BNF	–12.6500000	–16.4169640	–8.8830360	0.0000062	significant

Basil Canopy Width

Comparison	diff	lwr	upr	p adj	Significance
regolith_RF – regolith_BNF	–0.4666667	–4.4039488	3.4706155	0.9827538	n.s.
soil_BNF – regolith_BNF	1.375	–2.3079902	5.0579902	0.6735932	n.s.
soil_RF – regolith_BNF	–1.1500000	–4.8329902	2.5329902	0.7767775	n.s.

soil_BNF – regolith_RF	1.8416667	–1.8413243	5.5246569	0.4567464	n.s.
soil_RF – regolith_RF	–0.6833333	–4.3663236	2.9996569	0.9394788	n.s.
soil_RF – soil_BNF	–2.5250000	–5.9347864	0.8847864	0.171113	marginally significant

Leaf Count



Tomato Leaf Count

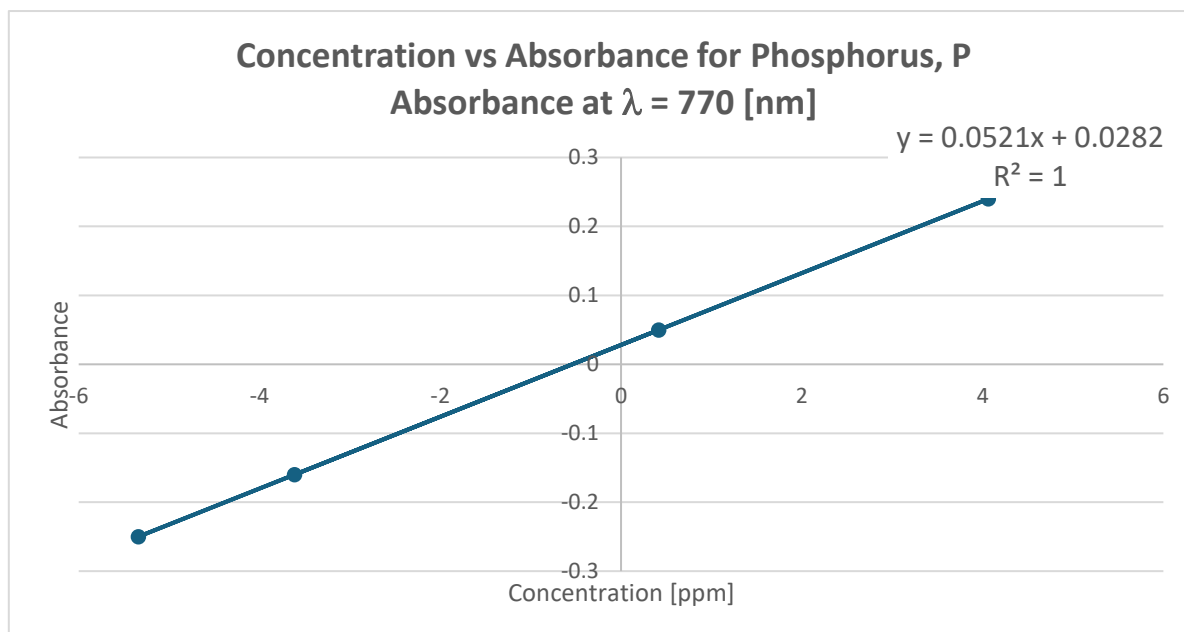
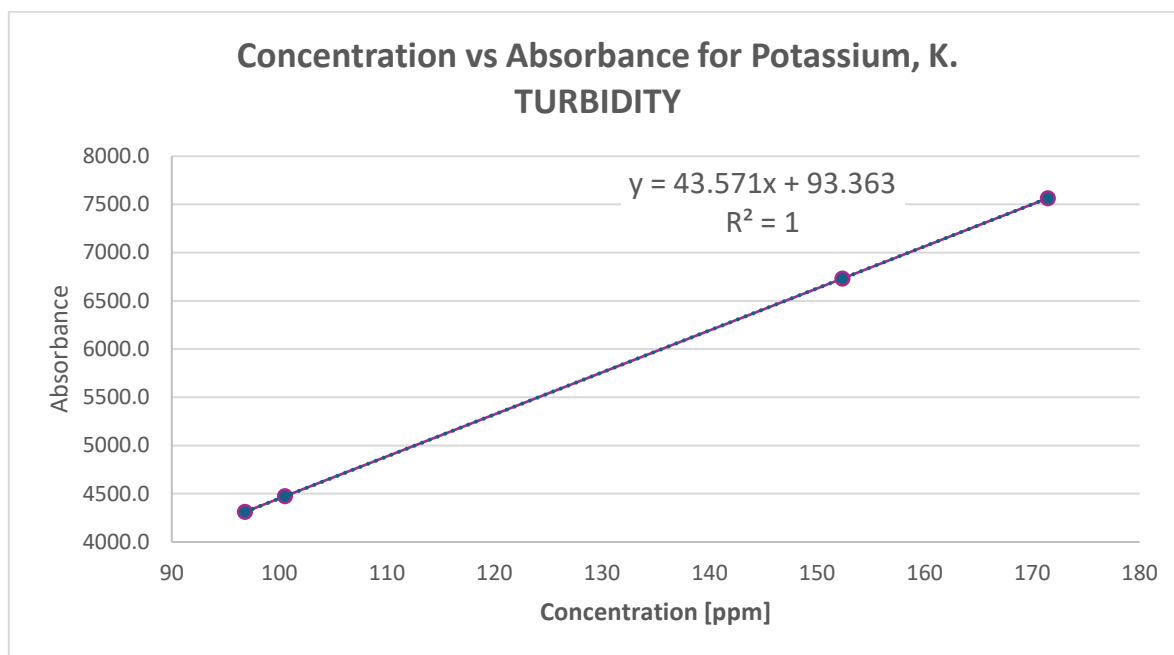
Comparison	diff	lwr	upr	p adj	Significance
regolith_RF – regolith_BNF	–1.0000000	–11.0934270	9.093427	0.9897351	n.s.
soil_BNF – regolith_BNF	16.2083333	6.7667974	25.6498693	0.0017604	significant
soil_RF – regolith_BNF	–2.4166667	–11.8582026	7.0248693	0.8604443	n.s.
soil_BNF – regolith_RF	17.2083333	7.7667974	26.6498693	0.0011226	significant
soil_RF – regolith_RF	–1.4166667	–10.8582026	8.0248693	0.9662938	n.s.
soil_RF – soil_BNF	–18.6250000	–27.3661640	–9.8838360	0.0003271	significant

Basil Leaf Count

Comparison	diff	lwr	upr	p adj	Significance
regolith_RF – regolith_BNF	–1.3333333	–7.4690173	4.8023506	0.9078998	n.s.
soil_BNF – regolith_BNF	0.3333333	–5.4060733	6.07274	0.9978713	n.s.
soil_RF – regolith_BNF	–2.1666667	–7.9060733	3.57274	0.6663123	n.s.
soil_BNF – regolith_RF	1.6666667	–4.0727400	7.4060733	0.810992	n.s.
soil_RF – regolith_RF	–0.8333333	–6.5727400	4.9060733	0.9692661	n.s.
soil_RF – soil_BNF	–2.5000000	–7.8136580	2.813658	0.5051329	n.s.

Nutrient Concentrations Across Treatments

Nutrient concentrations of nitrogen (N), phosphorus (P), and potassium (K) were quantified for four treatment groups: Regolith Banana Fertilizer (Reg BF), Soil Banana Fertilizer (Soil BF), Regolith Regular Fertilizer (Reg RF), and Soil Regular Fertilizer (Soil RF). Concentrations were calculated from spectrophotometric absorbance values using nutrient-specific calibration curves.



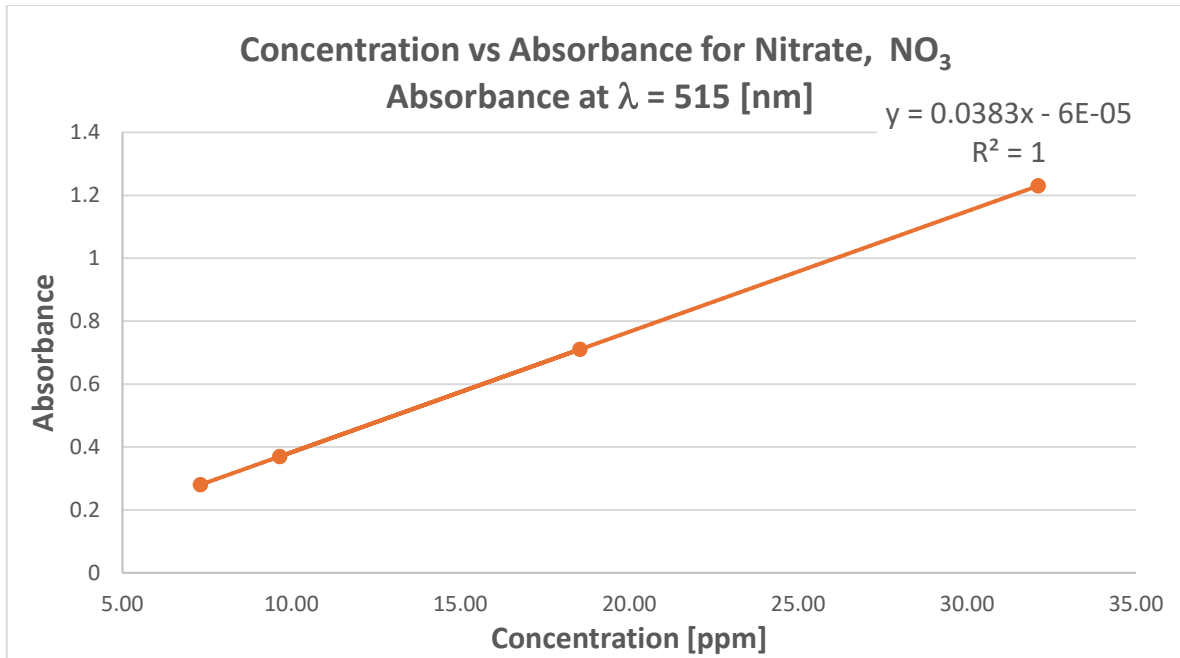


Table 1 summarizes the measured concentrations for nitrate, phosphorus, and potassium in each treatment.

Table 1. Measured nutrient concentrations (ppm) across treatments

Treatment	Nitrate (ppm)	Phosphorus (ppm)	Potassium (ppm)
Soil + Banana Fertilizer	32.11	0.4184	171.48
Regolith + Banana Fertilizer	9.66	-5.34	152.37
Soil + Regular Fertilizer	18.54	4.0653	100.54
Regolith + Regular Fertilizer	7.31	-3.612	96.80

Effect of Substrate on Nutrient Availability

Soil-based treatments exhibited higher nitrate concentrations than regolith-based treatments for both fertilizer types. The highest nitrate concentration was observed in **Soil + Banana Fertilizer** (32.11 ppm), whereas the lowest was measured in **Regolith + Regular Fertilizer** (7.31 ppm). This pattern suggests that soil provides a more favorable medium for nitrogen retention than regolith.

A similar substrate-related trend was observed for phosphorus, although the regolith treatments yielded negative calculated values. These values are not physically meaningful and likely indicate concentrations below the detection limit or the presence of matrix-related interference.

For potassium, both soil and regolith treatments amended with banana fertilizer showed substantially higher concentrations than their regular fertilizer counterparts. The highest potassium concentration was measured in **Soil + Banana Fertilizer** (171.48 ppm), followed by **Regolith + Banana Fertilizer** (152.37 ppm). In contrast, **Soil + Regular Fertilizer** and **Regolith + Regular Fertilizer** showed lower potassium concentrations of 100.54 ppm and 96.80 ppm, respectively.

Effect of Fertilizer Type

Banana-derived fertilizer resulted in higher nitrate and potassium concentrations than regular fertilizer in both substrates. In soil, nitrate increased from 18.54 ppm with regular fertilizer to 32.11 ppm with banana fertilizer, while potassium increased from 100.54 ppm to 171.48 ppm. In regolith, nitrate increased from 7.31 ppm to 9.66 ppm, and potassium increased from 96.80 ppm to 152.37 ppm.

These results suggest that the banana-based fertilizer may provide a greater supply of readily measurable nitrogen and potassium than the regular fertilizer under the tested conditions.

Phosphorus Measurement Limitations

Phosphorus measurements showed greater variability than nitrate and potassium. While positive phosphorus concentrations were obtained for the soil treatments, the regolith treatments produced negative calculated values. These results likely reflect concentrations below the calibration range, baseline noise, or matrix interference associated with regolith extracts. Therefore, phosphorus data from regolith treatments should be interpreted with caution.

■ Discussion and Conclusions

Enhanced Plant Growth with Banana Fertilizer

The results of this study demonstrate that banana fertilizer (BF) promotes enhanced plant growth compared to regular fertilizer (RF), particularly in soil systems and, to a slighter extent, in regolith. This trend is supported by both plant growth observations and quantitative nutrient analysis.

Specifically, nitrate concentrations were highest in Soil + BF (**32.11 ppm**) compared to Soil + RF (**18.54 ppm**), while regolith treatments showed lower but consistent increases with BF (**9.66 ppm**) relative to RF (**7.31 ppm**). Similarly, potassium concentrations were substantially higher in BF treatments, reaching **171.48 ppm** in soil and **152.37 ppm** in regolith, compared to **100.54 ppm** and **96.80 ppm**, respectively, in RF treatments.

These results indicate that BF enhances nutrient availability, particularly for nitrogen and potassium, which directly influence shoot and leaf development. Although the experimental duration was limited to five weeks, the observed differences suggest that BF provides a more effective nutrient delivery mechanism during early plant growth stages.

Mechanisms Behind Banana Fertilizer Performance

The superior performance of BF can be attributed to several interacting mechanisms:

- **High potassium availability:** Elevated potassium concentrations (up to 171.48 ppm) likely contributed to improved plant physiological performance, including water regulation, enzyme activation, and photosynthesis.
- **Improved nitrogen availability:** Higher nitrate concentrations in BNF treatments (up to 32.11 ppm) suggest enhanced nitrogen supply, a critical factor in vegetative growth.
- **Slow-release behavior:** Unlike RF, which provides nutrients in highly soluble forms, BF likely releases nutrients gradually through organic matter decomposition, reducing leaching losses.

- **Organic matter interactions:** Organic compounds in BF may increase water retention, enhance microbial activity, and facilitate nutrient stabilization through organo-mineral interactions.

These combined effects provide a mechanistic explanation for the increased growth observed in BF treatments.

Substrate Limitations and Regolith Behavior

As hypothesized, soil outperformed regolith in terms of nutrient retention and plant growth. This is reflected in consistently higher nitrate concentrations in soil treatments (32.11 ppm vs. 9.66 ppm for BF: 18.54 ppm vs. 7.31 ppm for RF).

The lower nutrient concentrations in regolith highlight its limited capacity to retain and supply nutrients, likely due to its lack of organic matter and low cation exchange capacity. Additionally, potassium concentrations, while elevated in BF treatments, remained slightly lower in regolith (152.37 ppm) compared to soil (171.48 ppm), further supporting the role of substrate structure in nutrient retention.

Despite these limitations, plant growth was achieved in regolith, demonstrating that it can support biological systems when supplemented with appropriate fertilizers.

Interaction Between Fertilizer Type and Substrate

The interaction between fertilizer type and substrate is critical in determining nutrient availability and plant growth. BF consistently resulted in higher nitrate and potassium concentrations than RF across both substrates.

A key observation was that in regolith, BF enabled early plant growth where RF did not produce measurable shoot growth during the initial stage of the experiment. This suggests that BF improves early-stage nutrient accessibility, particularly in nutrient-poor substrates.

However, the relative difference between BF and RF was smaller in regolith than in soil, indicating that substrate limitations constrain the effectiveness of fertilizer amendments.

Crop-Specific Responses

Differences in growth between plant species were observed, with tomato plants showing substantially greater growth than basil under identical experimental conditions. This suggests that plant response to substrate and fertilizer type is species dependent.

Nutrient data support this observation. BF treatments provided higher nitrate (up to 32.11 ppm in soil and 9.66 ppm in regolith) and potassium concentrations (up to 171.48 ppm in soil and 152.37 ppm in regolith), which are essential for plant growth. The enhanced growth of tomato plants may therefore reflect higher nutrient use efficiency (NUE), particularly for nitrogen.

In contrast, basil exhibited comparatively lower growth, suggesting differences in nutrient uptake capacity, metabolic demand, or root system development. These findings emphasize the importance of crop selection for optimizing growth in regolith-based systems.

Phosphorus Measurement Limitations

Phosphorus results showed inconsistencies, including negative values in regolith treatments (−5.34 ppm and −3.612 ppm), which are not physically meaningful. These values likely indicate concentrations below the detection limit or interference from the regolith matrix.

In contrast, soil treatments yielded measurable phosphorus concentrations (0.4184 ppm for BF and 4.0653 ppm for RF), suggesting that phosphorus is more reliably retained and detected in soil systems.

Future studies should refine analytical methods to improve phosphorus quantification, particularly in complex substrates such as regolith.

Experimental Limitations and Future Work

Several limitations should be considered:

- Short experimental duration (five weeks) limits long-term conclusions

- Lack of root system analysis (length, thickness, nutrient uptake efficiency) future work.
- Phosphorus detection limitations in regolith

Future work should extend the experimental timeline, include full growth cycles, and investigate alternative nutrient delivery strategies.

▪ **Conclusions**

This study demonstrates that banana-derived fertilizer is an effective organic amendment that enhances plant growth in both soil and regolith systems. Quantitative analysis showed that BF significantly increased nitrate (up to 32.11 ppm) and potassium (up to 171.48 ppm) concentrations compared to regular fertilizer.

While soil remains a more efficient substrate for plant growth, regolith was able to support plant development when supplemented with BF. These findings suggest that organic fertilizers derived from waste materials, such as banana peels, can improve nutrient availability and partially overcome the limitations of nutrient-poor substrates.

The results have important implications for sustainable agriculture in extraterrestrial environments, where in situ resource utilization and waste recycling will be essential. The ability of BF to enhance nutrient availability and support early plant growth suggests its potential application in future space missions, including the Artemis program.

Overall, this study provides evidence that organic amendments can play a critical role in enabling plant growth in regolith-based systems and represents a step toward the development of self-sustaining agricultural systems for space exploration.

■ Acknowledgements

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■ References

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Preparation of nano-fertilizer blend from banana peels. Bulletin of the National Research Centre, 43:26, 2019, <https://doi.org/10.1186/s42269-019-0058-1>

NASA. (2025). *What is lunar regolith? The Moon's surface explained*. NASA Biological & Physical Sciences. <https://science.nasa.gov/biological-physical/what-is-lunar-regolith/>

■ TEAM Artemis2



■ APPENDICES(R coding)

```
library(ggplot2)
```

```
##Reading the CSV file
```

```
data_t <-read.csv("data_t.csv")
```

```
data_b <-read.csv("data_b.csv")
```

```
##Setting functions for table
```

```
# ---- Tomato----
```

```
num_col_tom <-names(data_t)[sapply(data_t,is.numeric)]
```

```
sum_stat_t <- function(x){
```

```
c(
```

```
mean=mean(x, na.rm= TRUE),
```

```
sd=sd(x, na.rm= TRUE),
```

```
var=var(x, na.rm= TRUE),
```

```
se= sd(x, na.rm=TRUE)/sqrt(sum(!is.na(x))))}
```

```

sum_vals_t <- aggregate(data_t[,num_col_tom],
by=list(treatment=data_t$treatment),
FUN=sum_stat_t)
smt <- do.call(data.frame,sum_vals_t)
write.csv(smt, "smtom.csv")

```

#----Basil----

```

num_col_bas <-names(data_b)[sapply(data_b,is.numeric)]
sum_stat_p <- function(x){
c(
mean=mean(x, na.rm= TRUE),
sd=sd(x, na.rm= TRUE),
var=var(x, na.rm= TRUE),
se= sd(x, na.rm=TRUE)/sqrt(sum(!is.na(x))))}
sum_vals_p <- aggregate(data_b[,num_col_bas],
by=list(treatment=data_b$treatment),
FUN=sum_stat_p)
smp <- do.call(data.frame,sum_vals_p)
write.csv(smp, "smbasi.csv")

```

##ANOVA and Tukey comparison

#Shoot_length_cm

```

aov_shoot_l_t <-aov(shoot_length_cm~ treatment_group, data=data_t)
aov_shlt_hsd_t <- (TukeyHSD(aov_shoot_l_t))
aov_shlt_hsd_t

```

```

aov_shoot_l_b <-aov(shoot_length_cm~ treatment_group, data=data_b)
aov_shlt_hsd_b <- (TukeyHSD(aov_shoot_l_b))
aov_shlt_hsd_b

```

#canopy_width_cm

```

aov_canopy_t <- aov(canopy_width_cm ~ treatment_group, data=data_t)
aov_canopy_hsd_t <- TukeyHSD(aov_canopy_t)
aov_canopy_hsd_t

```

```

aov_canopy_b <- aov(canopy_width_cm ~ treatment_group, data=data_b)
aov_canopy_hsd_b <- TukeyHSD(aov_canopy_b)
aov_canopy_hsd_b

```

#leaf_count

```
aov_leaf_t <- aov(leaf_count ~ treatment_group, data=data_t)
aov_leaf_hsd_t <- TukeyHSD(aov_leaf_t)
aov_leaf_hsd_t
```

```
aov_leaf_b <- aov(leaf_count ~ treatment_group, data=data_b)
aov_leaf_hsd_b <- TukeyHSD(aov_leaf_b)
aov_leaf_hsd_b
```

```
##Visualization
```

```
# ---- Tomato (tomato) ----
```

```
plot_tsl <- ggplot(data_t, aes(x=treatment_group, y=shoot_length_cm)) +
  stat_summary(fun="mean", geom="col", fill="tomato") +
  stat_summary(fun.data=mean_se, geom="errorbar", width=0.1) +
  labs(title = "Tomato", x = "Treatment", y = "Mean Shoot Length (cm)") +
  scale_x_discrete(
    limits = c("soil_RF", "soil_BNF", "regolith_RF", "regolith_BNF"),
    labels = c(
      "regolith_BNF" = "Regolith(BNF)",
      "regolith_RF" = "Regolith(RF)",
      "soil_BNF" = "Soil(BNF)",
      "soil_RF" = "Soil(RF)"
    )
  ) + theme(plot.title = element_text(hjust = 0.5))
ggsave("plot_tsl.png", plot=plot_tsl, width=1800, height=1200, units="px")
```

```
plot_tcw <- ggplot(data_t, aes(x=treatment_group, y=canopy_width_cm)) +
  stat_summary(fun="mean", geom="col", fill="tomato") +
  stat_summary(fun.data=mean_se, geom="errorbar", width=0.1) +
  labs(title = "Tomato", x = "Treatment", y = "Mean Canopy Width (cm)") +
  scale_x_discrete(
    limits = c("soil_RF", "soil_BNF", "regolith_RF", "regolith_BNF"),
    labels = c(
      "regolith_BNF" = "Regolith(BNF)",
      "regolith_RF" = "Regolith(RF)",
      "soil_BNF" = "Soil(BNF)",
      "soil_RF" = "Soil(RF)"
    )
  ) + theme(plot.title = element_text(hjust = 0.5))
ggsave("plot_tcw.png", plot=plot_tcw, width=1800, height=1200, units="px")
```

```
plot_tlc <- ggplot(data_t, aes(x=treatment_group, y=leaf_count)) +
  stat_summary(fun="mean", geom="col", fill="tomato") +
```

```

stat_summary(fun.data=mean_se,geom="errorbar",width=0.1) +
labs(title = "Tomato", x = "Treatment", y = "Mean Leaf Count") +
scale_x_discrete(
  limits = c("soil_RF", "soil_BNF", "regolith_RF", "regolith_BNF"),
  labels = c(
    "regolith_BNF" = "Regolith(BNF)",
    "regolith_RF" = "Regolith(RF)",
    "soil_BNF" = "Soil(BNF)",
    "soil_RF" = "Soil(RF)"
  ))+theme(plot.title = element_text(hjust = 0.5))
ggsave("plot_tlc.png",plot=plot_tlc,width=1800,height=1200,units="px")

```

```

# ---- Basil (darkolivegreen4) ----
plot_bsl <-ggplot(data_b,aes(x=treatment_group, y=shoot_length_cm)) +
stat_summary(fun="mean", geom="col",fill="darkolivegreen4") +
stat_summary(fun.data=mean_se,geom="errorbar",width=0.1) +
labs(title = "Basil", x = "Treatment", y = "Mean Shoot Length (cm)") +
scale_x_discrete(
  limits = c("soil_RF", "soil_BNF", "regolith_RF", "regolith_BNF"),
  labels = c(
    "regolith_BNF" = "Regolith(BNF)",
    "regolith_RF" = "Regolith(RF)",
    "soil_BNF" = "Soil(BNF)",
    "soil_RF" = "Soil(RF)"
  ))+theme(plot.title = element_text(hjust = 0.5))
ggsave("plot_bsl.png",plot=plot_bsl,width=1800,height=1200,units="px")

```

```

plot_bcw <-ggplot(data_b,aes(x=treatment_group, y=canopy_width_cm)) +
stat_summary(fun="mean", geom="col",fill="darkolivegreen4") +
stat_summary(fun.data=mean_se,geom="errorbar",width=0.1) +
labs(title = "Basil", x = "Treatment", y = "Mean Canopy Width (cm)") +
scale_x_discrete(
  limits = c("soil_RF", "soil_BNF", "regolith_RF", "regolith_BNF"),
  labels = c(
    "regolith_BNF" = "Regolith(BNF)",
    "regolith_RF" = "Regolith(RF)",
    "soil_BNF" = "Soil(BNF)",
    "soil_RF" = "Soil(RF)"
  ))+theme(plot.title = element_text(hjust = 0.5))
ggsave("plot_bcw.png",plot=plot_bcw,width=1800,height=1200,units="px")

```

```

plot_blc <-ggplot(data_b,aes(x=treatment_group, y=leaf_count)) +
  stat_summary(fun="mean", geom="col",fill="darkolivegreen4") +
  stat_summary(fun.data=mean_se,geom="errorbar",width=0.1) +
  labs(title = "Basil", x = "Treatment", y = "Mean Leaf Count") +
  scale_x_discrete(
    limits = c("soil_RF", "soil_BNF", "regolith_RF", "regolith_BNF"),
    labels = c(
      "regolith_BNF" = "Regolith(BNF)",
      "regolith_RF" = "Regolith(RF)",
      "soil_BNF" = "Soil(BNF)",
      "soil_RF" = "Soil(RF)"
    )
  )+theme(plot.title = element_text(hjust = 0.5))
ggsave("plot_blc.png",plot=plot_blc,width=1800,height=1200,units="px")

```

■ Appendix B. Experiment Photos

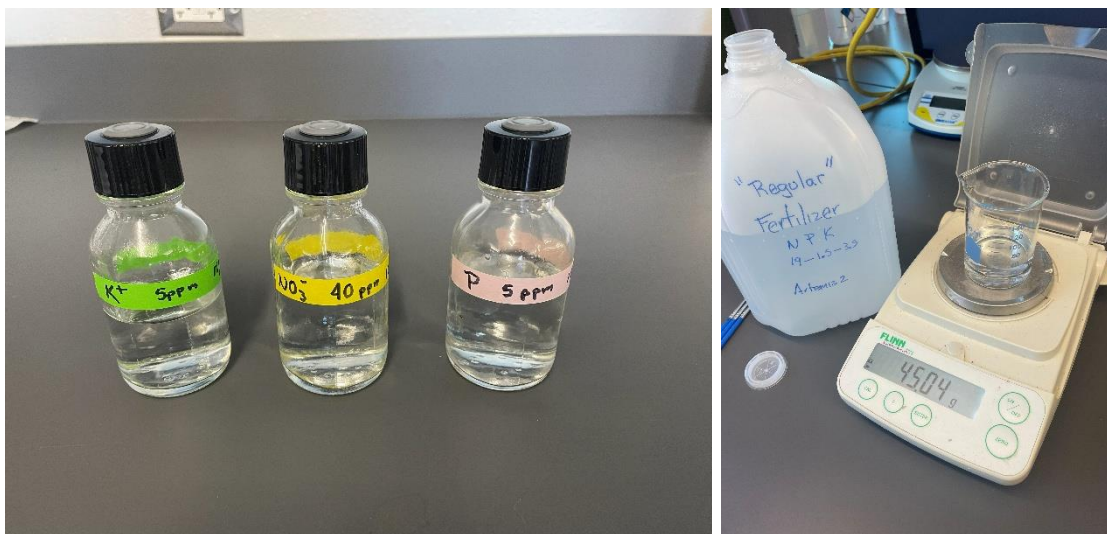


Figure 4. RF preparation



Figure 5. BNF preparation



Figure 6. Initial germination

ARTEMIS

1 SOIL		2 REGOLITH	
R.F. 1	N.F. 2	1 R.F.	2 N.F.
1. Tomato	1. Tomato	1. Tomato	1. Tomato
2. Tomato	2. Tomato	2. Tomato	2. Tomato
3. Tomato	3. Tomato	3. Tomato	3. Tomato
4. Basil	4. Basil	4. Basil	4. Basil
5. Basil	5. Basil	5. Basil	5. Basil
6. Basil	6. Basil	6. Basil	6. Basil

16 12

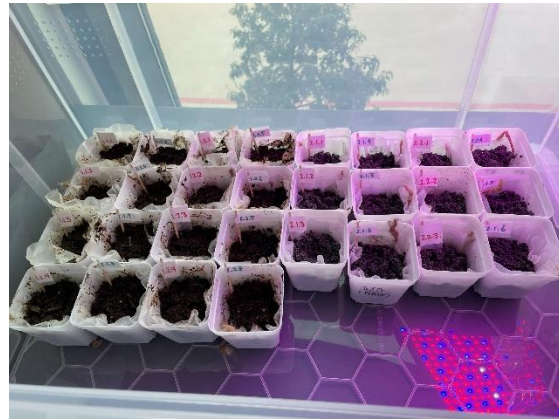


Figure 7. Plant numbering system



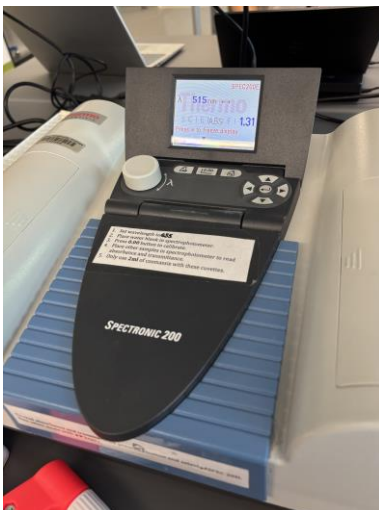
Figure 8. Photos showing Final Replanting



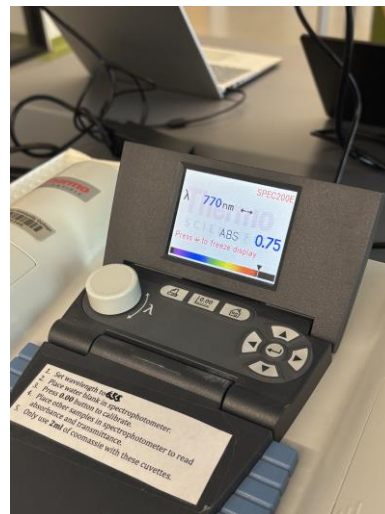
Figure 9. Preparing for the extraction identification of nutrient amount.



(zeroing spectrophotometer with DI water)



Nitrogen



Potassium



Phosphorus

Figure 10. Nutrient Analysis

■ Appendix C. Raw Data

date (yyyy/mm/dd)	uid	treatment group	species	shoot length [cm]	canopy width [cm]	leaf count
2026/03/05	1.1.1	soil_RF	Tomato	3.5		
2026/03/05	1.1.2	soil_RF	Tomato	2.4		
2026/03/05	1.1.3	soil_RF	Tomato	5		
2026/03/05	1.1.4	soil_RF	Tomato	1.8		
2026/03/05	1.1.5	soil_RF	Basil	0.4		
2026/03/05	1.1.6	soil_RF	Basil	0.8		
2026/03/05	1.1.7	soil_RF	Basil	0.5		
2026/03/05	1.1.8	soil_RF	Basil	1		
2026/03/05	1.2.1	soil_BNF	Tomato	4.5		
2026/03/05	1.2.2	soil_BNF	Tomato	4.5		
2026/03/05	1.2.3	soil_BNF	Tomato	4.5		
2026/03/05	1.2.4	soil_BNF	Tomato	3.5		
2026/03/05	1.2.5	soil_BNF	Basil	1.8		
2026/03/05	1.2.6	soil_BNF	Basil	1.4		
2026/03/05	1.2.7	soil_BNF	Basil	1.2		
2026/03/05	1.2.8	soil_BNF	Basil	1.5		
2026/03/05	2.1.1	regolith_RF	Tomato	0		
2026/03/05	2.1.2	regolith_RF	Tomato	0		
2026/03/05	2.1.3	regolith_RF	Tomato	0		
2026/03/05	2.1.4	regolith_RF	Basil	0		
2026/03/05	2.1.5	regolith_RF	Basil	0		
2026/03/05	2.1.6	regolith_RF	Basil	0		
2026/03/05	2.2.1	regolith_BNF	Tomato	3.5		
2026/03/05	2.2.2	regolith_BNF	Tomato	5		
2026/03/05	2.2.3	regolith_BNF	Tomato	1.8		
2026/03/05	2.2.4	regolith_BNF	Basil	0.9		
2026/03/05	2.2.5	regolith_BNF	Basil	0.8		
2026/03/05	2.2.6	regolith_BNF	Basil	1.3		
2026/03/10	1.1.1	soil_RF	Tomato	5		
2026/03/10	1.1.2	soil_RF	Tomato	3.1		
2026/03/10	1.1.3	soil_RF	Tomato	5.7		
2026/03/10	1.1.4	soil_RF	Tomato	2.7		
2026/03/10	1.1.5	soil_RF	Basil	1.5		
2026/03/10	1.1.6	soil_RF	Basil	1.5		
2026/03/10	1.1.7	soil_RF	Basil	1.5		
2026/03/10	1.1.8	soil_RF	Basil	1.1		
2026/03/10	1.2.1	soil_BNF	Tomato	4.4		

2026/03/10	1.2.2	soil_BNF	Tomato	4.5		
2026/03/10	1.2.3	soil_BNF	Tomato	4		
2026/03/10	1.2.4	soil_BNF	Tomato	3		
2026/03/10	1.2.5	soil_BNF	Basil	1.8		
2026/03/10	1.2.6	soil_BNF	Basil	1		
2026/03/10	1.2.7	soil_BNF	Basil	0.9		
2026/03/10	1.2.8	soil_BNF	Basil	1.8		
2026/03/10	2.1.1	regolith_RF	Tomato	4		
2026/03/10	2.1.2	regolith_RF	Tomato	1.5		
2026/03/10	2.1.3	regolith_RF	Tomato	4.4		
2026/03/10	2.1.4	regolith_RF	Basil	0.3		
2026/03/10	2.1.5	regolith_RF	Basil	1		
2026/03/10	2.1.6	regolith_RF	Basil	1		
2026/03/10	2.2.1	regolith_BNF	Tomato	3.5		
2026/03/10	2.2.2	regolith_BNF	Tomato	4.6		
2026/03/10	2.2.3	regolith_BNF	Tomato	1.7		
2026/03/10	2.2.4	regolith_BNF	Basil	1		
2026/03/10	2.2.5	regolith_BNF	Basil	0.6		
2026/03/10	2.2.6	regolith_BNF	Basil	1.8		
2026/03/26	1.1.1	soil_RF	Tomato	4.3		
2026/03/26	1.1.2	soil_RF	Tomato	3.2		
2026/03/26	1.1.3	soil_RF	Tomato	4.5		
2026/03/26	1.1.4	soil_RF	Tomato	3.4		
2026/03/26	1.1.5	soil_RF	Basil	4		
2026/03/26	1.1.6	soil_RF	Basil	1.3		
2026/03/26	1.1.7	soil_RF	Basil	1		
2026/03/26	1.1.8	soil_RF	Basil	1.5		
2026/03/26	1.2.1	soil_BNF	Tomato	7		
2026/03/26	1.2.2	soil_BNF	Tomato	7.45		
2026/03/26	1.2.3	soil_BNF	Tomato	5.7		
2026/03/26	1.2.4	soil_BNF	Tomato	6.3		
2026/03/26	1.2.5	soil_BNF	Basil	3		
2026/03/26	1.2.6	soil_BNF	Basil	1.5		
2026/03/26	1.2.7	soil_BNF	Basil	3.5		
2026/03/26	1.2.8	soil_BNF	Basil	1.5		
2026/03/26	2.1.1	regolith_RF	Tomato	4		
2026/03/26	2.1.2	regolith_RF	Tomato	2.6		
2026/03/26	2.1.3	regolith_RF	Tomato	5		
2026/03/26	2.1.4	regolith_RF	Basil	0.3		
2026/03/26	2.1.5	regolith_RF	Basil	0.8		
2026/03/26	2.1.6	regolith_RF	Basil	1.3		

2026/03/26	2.2.1	regolith_BNF	Tomato	5.5		
2026/03/26	2.2.2	regolith_BNF	Tomato	6.6		
2026/03/26	2.2.3	regolith_BNF	Tomato	4.7		
2026/03/26	2.2.4	regolith_BNF	Basil	1.4		
2026/03/26	2.2.5	regolith_BNF	Basil	1.7		
2026/03/26	2.2.6	regolith_BNF	Basil	1.7		
2026/04/01	1.1.1	soil_RF	Tomato	5.3		
2026/04/01	1.1.2	soil_RF	Tomato	4.2		
2026/04/01	1.1.3	soil_RF	Tomato	6.2		
2026/04/01	1.1.4	soil_RF	Tomato	4.8		
2026/04/01	1.1.5	soil_RF	Basil	0		
2026/04/01	1.1.6	soil_RF	Basil	2		
2026/04/01	1.1.7	soil_RF	Basil	1.8		
2026/04/01	1.1.8	soil_RF	Basil	1.4		
2026/04/01	1.2.1	soil_BNF	Tomato	7.6		
2026/04/01	1.2.2	soil_BNF	Tomato	8.9		
2026/04/01	1.2.3	soil_BNF	Tomato	8		
2026/04/01	1.2.4	soil_BNF	Tomato	8		
2026/04/01	1.2.5	soil_BNF	Basil	3.9		
2026/04/01	1.2.6	soil_BNF	Basil	1.5		
2026/04/01	1.2.7	soil_BNF	Basil	3.7		
2026/04/01	1.2.8	soil_BNF	Basil	1.6		
2026/04/01	2.1.1	regolith_RF	Tomato	5.9		
2026/04/01	2.1.2	regolith_RF	Tomato	4.1		
2026/04/01	2.1.3	regolith_RF	Tomato	6		
2026/04/01	2.1.4	regolith_RF	Basil	0.9		
2026/04/01	2.1.5	regolith_RF	Basil	1.1		
2026/04/01	2.1.6	regolith_RF	Basil	1.3		
2026/04/01	2.2.1	regolith_BNF	Tomato	6.4		
2026/04/01	2.2.2	regolith_BNF	Tomato	7.4		
2026/04/01	2.2.3	regolith_BNF	Tomato	5		
2026/04/01	2.2.4	regolith_BNF	Basil	1.3		
2026/04/01	2.2.5	regolith_BNF	Basil	1.8		
2026/04/01	2.2.6	regolith_BNF	Basil	2.1		
2026/04/07	1.1.1	soil_RF	Tomato	5	2.5	4
2026/04/07	1.1.2	soil_RF	Tomato	4.3	2.5	6
2026/04/07	1.1.3	soil_RF	Tomato	6.8	4.3	7
2026/04/07	1.1.4	soil_RF	Tomato	5	2.8	8
2026/04/07	1.1.5	soil_RF	Basil	0	0	0
2026/04/07	1.1.6	soil_RF	Basil	1.4	0.7	2
2026/04/07	1.1.7	soil_RF	Basil	1.7	1.7	4

2026/04/07	1.1.8	soil_RF	Basil	1.3	2.2	4
2026/04/07	1.2.1	soil_BNF	Tomato	9.8	14.8	21
2026/04/07	1.2.2	soil_BNF	Tomato	11.5	18.4	21.5
2026/04/0	1.2.3	soil_BNF	Tomato	12.5	12.1	22
2026/04/07	1.2.4	soil_BNF	Tomato	12.2	17.4	35
2026/04/07	1.2.5	soil_BNF	Basil	4	5.2	4
2026/04/07	1.2.6	soil_BNF	Basil	0	0	0
2026/04/07	1.2.7	soil_BNF	Basil	5.2	5.8	8
2026/04/07	1.2.8	soil_BNF	Basil	2	3.7	8
2026/04/07	2.1.1	regolith_RF	Tomato	5.2	3.5	8
2026/04/07	2.1.2	regolith_RF	Tomato	4.5	2.5	5
2026/04/07	2.1.3	regolith_RF	Tomato	6.1	3	10
2026/04/07	2.1.4	regolith_RF	Basil	0.9	1.7	4
2026/04/07	2.1.5	regolith_RF	Basil	2	1.8	4
2026/04/07	2.1.6	regolith_RF	Basil	1.7	2	2
2026/04/07	2.2.1	regolith_BNF	Tomato	7.4	6.2	9
2026/04/07	2.2.2	regolith_BNF	Tomato	9	4.9	10
2026/04/07	2.2.3	regolith_BNF	Tomato	5.1	3.5	7
2026/04/07	2.2.4	regolith_BNF	Basil	1.4	1.7	4
2026/04/07	2.2.5	regolith_BNF	Basil	1.7	3.3	4
2026/04/07	2.2.6	regolith_BNF	Basil	2.1	1.9	6