LUNAR DUST FILTRATION STUDY

Formal Laboratory Protocol

HEPA and Low-Cost Filter Effectiveness Against
Lunar Dust Simulant Aerosols

Subject Area	Aerospace Health & Engineering
Level	High School / Introductory Undergraduate
Duration	3 lab sessions (90 min each) + analysis
Group Size	3–4 students per group
Estimated Cost	$40–$120 per group (Tier 2) or $5–$15 (Tier 3)

Prepared for Classroom Use — Artemis Generation Science Series

1. Laboratory Overview

This experiment investigates how effectively different types of filters capture fine particulate matter from aerosolized lunar dust simulant. Students will build a sealed test chamber, aerosolize a lunar simulant using a fluidized bed or impulse injection method, and measure particle concentrations upstream and downstream of various filter materials using either a low-cost optical sensor or gravimetric (mass-based) analysis.

By comparing multiple filter types — HEPA, MERV-rated, and improvised alternatives — students will calculate real filtration efficiency percentages and draw conclusions about which materials could protect astronauts living and working on the Moon.

> **ℹ Learning Objectives**
> - Understand why lunar dust is a unique respiratory hazard compared to terrestrial dust
> - Design a controlled experiment with clear independent, dependent, and controlled variables
> - Build and calibrate a functional aerosolization and sampling apparatus
> - Collect quantitative particle data and calculate filtration efficiency
> - Analyze cost-vs-performance tradeoffs relevant to real space mission engineering
> - Communicate findings through data tables, graphs, and a formal lab report

1.1 Background

Lunar dust (regolith fines < 20 μm) is one of the most serious health threats facing future astronauts on the Moon. Unlike Earth dust, it has never been rounded by wind or water erosion. Its particles are razor-sharp, electrostatically charged, and rich in silicates — properties that allow it to penetrate deep into lung tissue and evade the body's natural clearing mechanisms. Apollo astronauts reported respiratory symptoms after just brief exposure inside their lunar module.

For long-duration Artemis missions, effective filtration inside habitats and vehicles is critical. NASA's own standards require HEPA-grade filtration (99.97% efficiency at 0.3 μm) for pressurized lunar cabin air. This experiment tests whether that standard is achievable with common materials — and what the cost and performance tradeoffs look like.

1.2 Research Questions

- Which filter type achieves the highest particle capture efficiency against lunar simulant dust?
- How does filtration efficiency change as a function of particle size (PM2.5 vs. PM10)?
- What is the cost-per-percent-efficiency of each filter option?
- Do improvised filter alternatives (cotton layers, coffee filters) approach the performance of commercial HEPA units?

1.3 Hypothesis

Write your group hypothesis here before beginning the experiment:

If ________________________ then ________________________ because ________________________.

2. Materials List

All costs are approximate retail estimates. Items marked with * are shared among the whole class; others are per-group.

2.1 Test Chamber Construction

Item	Quantity	Est. Cost	Source
Clear PVC or acrylic pipe, 4" diameter × 24" long	1 per group	$8–$12	Hardware store
PVC end caps (4"), drilled with 1" center hole	2 per group	$4–$6	Hardware store
PVC primer and cement	1 can*	$6–$8 shared	Hardware store
Aquarium air pump (small, ~1.5 L/min)	1 per group	$8–$12	Pet store / Amazon
Flexible vinyl tubing, 1/4" ID × 3 ft	1 per group	$3–$5	Hardware store
Rubber stoppers (2-hole, #5 or #6)	2 per group	$3–$5	Lab supply
Silicone sealant / aquarium-safe caulk	1 tube*	$5–$7 shared	Hardware store
Hose clamps (1" diameter)	4 per group	$4	Hardware store
Digital anemometer or rotameter (flow meter)*	1 shared	$15–$25 shared	Amazon

2.2 Simulant and Aerosolization

Item	Quantity	Est. Cost	Source
Exolith LHS-1 lunar simulant (highland, fine grade) OR LMS-1 (mare)	100 g per group	~$20–$30*	exolithlab.com
Fine ground volcanic basalt (budget alternative to LHS-1)	200 g per group	$5–$10*	Art supply / Amazon
Wire mesh / perforated sheet (60-mesh, for fluidized bed base)	6" × 6" piece*	$3–$6 shared	Hardware store
Small plastic container (500 mL) for fluidized bed chamber	1 per group	$2–$3	Dollar store
Pre-weighed 60 mL plastic syringes (for impulse injection, Tier 3)	2 per group	$2–$4	Lab supply
Weighing boat / weigh paper	pkg of 20*	$3–$5 shared	Lab supply / Amazon
Analytical balance (0.0001 g resolution)*	1 shared	Lab equipment	School lab

2.3 Filters Under Test

Filter Material	Rating	Est. Cost	Source	Label

True HEPA filter (cut from room air purifier)	H13 (99.95%)	$15–$25*	Hardware store	**Filter A**
MERV-13 HVAC filter (cut to size)	MERV-13	$10–$15*	Hardware store	**Filter B**
MERV-8 HVAC filter (cut to size)	MERV-8	$5–$8*	Hardware store	**Filter C**
Surgical face mask material (3-ply)	~95% (BFE)	$0.10–$0.25	Pharmacy	**Filter D**
Two layers of 100% cotton muslin	Unknown (test it!)	$1–$2	Fabric store	**Filter E**
Two layers of standard coffee filter	Unknown (test it!)	< $0.25	Grocery store	**Filter F**
No filter (open tube — control)	0%	$0	—	**Control**

2.4 Measurement Equipment

Item	Tier	Est. Cost	Purpose
Plantower PMS5003 or PMS7003 particulate sensor	**Tier 2**	$18–$28	PM2.5/PM10 optical counting
Arduino Uno or Nano microcontroller	**Tier 2**	$10–$20	Data logging
USB cable + laptop for Serial Monitor	**Tier 2**	$0 (school)	Read sensor output
Mixed cellulose ester (MCE) membrane filter discs, 0.8 µm, 47 mm*	**Tier 3**	$15–$25/pkg	Gravimetric capture
Filter holders (47 mm Swinnex or in-line)*	**Tier 3**	$8–$15	Hold membranes in airstream
Analytical balance (0.0001 g resolution)*	Both	School lab	Weigh membranes
Stopwatch or phone timer	Both	$0	Timed exposure runs
Spreadsheet software (Excel or Google Sheets)	Both	$0	Data recording and graphing

3. Safety Procedures

Fine particulate work requires strict safety protocols at all times. Lunar simulants are silicate-based minerals that can cause lung damage if inhaled. Read all safety rules before touching any materials.

⚠ STOP — Required Before Any Lab Work

- Every student must wear a properly fitted N95 respirator mask at ALL times when simulant is handled, open, or aerosolized. A surgical mask is NOT sufficient.
- Safety goggles (not glasses) must be worn throughout all sessions when simulant is present.
- Nitrile gloves must be worn when handling simulant, used filters, or membrane discs.
- All aerosolization must occur inside a laminar flow fume hood or sealed enclosure — NEVER in open room air. (The fume hood should be purged prior to use and your teacher should know that you are using the fume hood. The teacher should give instructions on use and approve your test prior to use)
- Students with asthma, respiratory conditions, or eye sensitivities must inform the instructor before participating. Alternative roles will be assigned.

3.1 Personal Protective Equipment (PPE) Required

PPE Item	Standard Required	When to Wear
N95 Respirator	NIOSH-approved N95 or better	Anytime simulant container is open or aerosolized
Safety goggles	ANSI Z87.1 rated, indirect vent	All lab sessions when simulant is present
Nitrile gloves	Any nitrile, any thickness	All simulant handling, filter removal, membrane weighing
Lab coat or old long-sleeve shirt	Cover skin, avoid cotton that traps dust	All sessions

3.2 Simulant Handling Rules

1. Always keep the simulant container capped when not actively dispensing.
2. Weigh and transfer simulant only inside the fume hood or sealed chamber.
3. Never blow on simulant with your mouth or allow compressed air near open containers.
4. If simulant spills, wet it lightly with a damp paper towel before wiping — do NOT sweep dry.
5. Dispose of used simulant, contaminated gloves, and spent filters in a sealed zip-lock bag, then in the regular trash (non-hazardous mineral simulant).
6. Wash hands thoroughly with soap and water after removing gloves at the end of each session.

3.3 Electrical Safety (Tier 2 — Arduino/Sensor)

7. Do not connect or disconnect the Arduino while it is powered via USB.
8. Ensure no wires contact the simulant or damp surfaces.
9. Use only 5V USB power — do not use wall adapters above 5V with the sensor.

10. If the sensor smells hot or produces smoke, disconnect USB immediately and notify the instructor.

3.4 Emergency Procedures

- Eye contact with simulant: Flush with running water for 15 minutes. Do NOT rub. Seek medical attention if irritation persists.
- Accidental inhalation (mask failure): Move to fresh air immediately. Inform instructor. Seek medical attention if coughing or irritation persists.
- Skin contact: Wash with soap and water. Simulant is not acutely toxic on skin, but abrasive.
- Emergency: School's emergency number is posted in the lab. Know where the eyewash station and first aid kit are located before starting.

4. Experimental Design

4.1 Variables

Variable Type	What It Is	How It Is Controlled
Independent variable	Filter material / type (A through F + control)	Swap filter between identical runs
Dependent variable	Particle concentration downstream of filter (counts/m³ or mg)	Measured by sensor or membrane mass
Controlled variables	Flow rate, simulant amount, run duration, upstream concentration, temperature	Fixed using pump setting, pre-weighed simulant, stopwatch

4.2 Simulant Choice and Rationale

Primary recommendation: Exolith LHS-1 or LMS-1 (fine grade). These are mineralogically accurate simulants made from crushed volcanic and anorthositic rock that match Apollo sample chemistry and particle shape. Their sharp, angular particle geometry replicates the hazard that makes real lunar dust dangerous.

Budget alternative: Fine-ground volcanic basalt (available as landscape or art supply material, ground to < 75 μm using a mortar and pestle or ball mill). This lacks the compositional precision of LHS-1 but captures the critical sharp silicate geometry at near-zero cost. Sieve to isolate the < 75 μm fraction before use.

> **ℹ Why not use real lunar regolith?**
>
> - Actual Apollo samples are tightly controlled by NASA and unavailable for student use.
> - Simulants approved for research replicate the physical hazard properties that matter for this experiment.
> - Volcanic basalt is a safe, low-cost proxy for the sharp silicate fraction responsible for respiratory damage.

4.3 Aerosolization Methods

Choose ONE method based on available equipment. Both produce adequate particle suspensions for this experiment.

Method A — Fluidized Bed (preferred for sustained, consistent exposure)

A fluidized bed suspends particles in a continuous upward airflow through a fine mesh screen, keeping them airborne for the duration of the run. This produces a stable, reproducible particle concentration that does not require repeated handling of simulant between runs.

Construction:

11. Cut a 6" circle of 60-mesh steel window screen and glue it 1/3 of the way up inside the plastic container using silicone sealant. Allow to cure 24 hours.

12. Drill a 1/4" hole in the bottom of the container and attach a vinyl tube fitting. Connect to the aquarium air pump.
13. Drill a 1/4" outlet hole near the top of the container and connect tubing to the inlet of the test chamber.
14. Place 1.0 g (pre-weighed) of simulant on top of the mesh screen inside the container.
15. Turn on the pump. Adjust flow until particles visibly lift and swirl above the mesh — this is the fluidization threshold. Note the flow setting and keep it constant for all runs.

Method B — Impulse Injection (budget option, no construction required)

A pre-charged syringe delivers a measured bolus of suspended dust directly into the test chamber inlet. This method is less steady-state but easier to set up and allows precise control of total dust input per run.

Procedure:

16. Pre-weigh exactly 0.10 g of simulant into each syringe using the analytical balance and a weigh boat. Cap the syringe.
17. Run the aquarium pump at a fixed flow rate through the chamber for 30 seconds to establish baseline airflow.
18. Unscrew the inlet cap, inject the syringe bolus in one sharp compression over ~2 seconds, immediately reseal.
19. Allow the pump to continue running for the full timed collection period (e.g., 5 minutes).
20. Use a fresh pre-weighed syringe for every run. Record the exact mass loaded into each syringe on your data sheet.

ℹ Key difference between methods

- Method A gives a steady-state concentration over time — better for Tier 2 sensor logging.
- Method B gives a single injection event with decaying concentration — works well with Tier 3 gravimetric collection.
- Whichever method your group uses, keep it IDENTICAL across all filter tests.

5. Particle Quantification Methods

Choose the tier that matches your available equipment. Both tiers yield valid, publishable-quality results when executed carefully. **Keep in mind you may want to add an additional test of multiple types of filters in a series, but this is not required.**

5.1 Tier 2 — Low-Cost Optical Particle Counter (OPC)

The Plantower PMS5003 uses laser light scattering to count and size particles in real time. It outputs PM1.0, PM2.5, and PM10 mass concentrations (µg/m³) via serial communication at 1-second intervals. This is the same technology used by air quality monitoring networks worldwide.

Sensor Setup (Arduino)

Wire the PMS5003 to the Arduino Uno using the following connections:

PMS5003 Pin	Arduino Pin
VCC (5V)	5V
GND	GND
TX (data out)	Pin 2 (SoftwareSerial RX)
RX (not needed)	Not connected

Upload the PMS5003 Arduino library sketch (available at: github.com/fu-hsi/pms) and open Serial Monitor at 9600 baud. The sensor outputs a reading every second. Allow the sensor to warm up for 30 seconds before recording data.

Sensor Placement

21. Drill two sampling ports into the side of the test chamber — one 3" from the inlet end (upstream) and one 3" from the outlet end (downstream).
22. Insert the sensor inlet tube snugly into each port using a rubber stopper. Seal any gaps with silicone.
23. For best results, use two identical sensors simultaneously — one upstream and one downstream — so both measurements are taken at the same moment.
24. If only one sensor is available, run two identical back-to-back trials: first with the sensor upstream, then downstream. Average the results.

Data Collection Procedure (Tier 2)

25. Start the pump and allow flow to stabilize for 30 seconds. Record baseline (zero-dust) upstream and downstream readings.
26. Begin aerosolization (Method A or B). Start a 5-minute timer.
27. Record PM2.5 and PM10 readings from both sensor positions every 30 seconds for the full 5 minutes.
28. After 5 minutes, stop aerosolization. Allow the pump to run 1 additional minute to clear the chamber.
29. Calculate mean upstream and mean downstream concentrations from the time-series data.

1. Swap the filter. Wait 2 minutes for the chamber to clear completely. Repeat steps 1–5 for each filter type.

Filtration Efficiency Calculation (Tier 2)

Filtration Efficiency (%) = [(C_upstream − C_downstream) / C_upstream] × 100

Where C = mean particle concentration (μg/m³) for PM2.5 or PM10

5.2 Tier 3 — Gravimetric (Mass-Based) Method

Gravimetric measurement is the oldest and most reliable form of particle quantification. You capture all particles passing through a known volume of air onto a pre-weighed membrane, then weigh it again after the run. The mass difference is the particle mass collected. No electronics required.

Membrane Preparation

2. Label two MCE membrane filter discs per run: one labeled 'UP' (upstream) and one 'DOWN' (downstream).
3. Place each disc in its labeled petri dish. Leave the lids off and allow to equilibrate at room temperature for 30 minutes (humidity affects weight).
4. Tare the analytical balance. Weigh each membrane to 0.0001 g precision. Record this as the tare weight on your data sheet.
5. Load each disc into its filter holder. Handle discs only with clean forceps — never fingers (skin oils add mass).

Sampling Setup

6. Install the upstream filter holder in the sampling port 3" from the inlet.
7. Install the downstream filter holder in the sampling port 3" from the outlet.
8. Install the test filter (A through F) between the two sampling ports in the filter stage.
9. Confirm all connections are sealed with silicone or tape. Air leaks invalidate the mass balance.

Data Collection Procedure (Tier 3)

10. Run the pump at the calibrated flow rate for 5 minutes with NO simulant to collect a blank. Weigh both membranes and record blank mass as baseline.
11. Reload fresh pre-weighed membranes. Begin aerosolization (Method A or B). Run for exactly 10 minutes. Use a stopwatch.
12. Stop aerosolization and the pump simultaneously. Immediately remove both membranes using forceps and return each to its labeled petri dish.
13. Cover the dishes and allow them to equilibrate for 30 minutes before weighing (same conditions as tare).
14. Weigh each membrane on the analytical balance to 0.0001 g. Record as post-exposure weight.
15. Calculate: Particle mass collected = post-exposure weight − tare weight.

Filtration Efficiency Calculation (Tier 3)

$$\text{Filtration Efficiency (\%)} = \left[\frac{M_{upstream} - M_{downstream}}{M_{upstream}} \right] \times 100$$

Where M = mass collected on membrane (mg), upstream minus blank

6. Step-by-Step Procedure

Session 1 — Build and Calibrate (90 min)

16. Assemble the test chamber from PVC pipe and end caps. Drill all ports and seal with silicone. Allow to cure overnight if using silicone cement.
17. Construct the fluidized bed (Method A) or load and cap the syringes (Method B).
18. Connect the aquarium pump to the chamber inlet. Run air through the empty chamber and verify flow with the anemometer. Record the flow rate (L/min). This will be your fixed flow rate for all trials.
19. Set up the particle sensor (Tier 2: wire Arduino and verify serial output) or prepare membranes (Tier 3: tare all membranes and load into holders).
20. Cut all filter materials to the correct size and shape for the filter stage. Label clearly.
21. Run a dry test with the control (no filter) to verify the system produces a detectable particle signal above baseline.

Session 2 — Data Collection (90 min)

22. Don all PPE before opening simulant container. Do not remove PPE until simulant is secured.
23. Begin with the control trial (no filter). Run for the full timed period and record all data on the student data sheet.
24. Run Filter A (HEPA). Clear the chamber, install the filter, repeat the full aerosolization run.
25. Repeat for Filters B, C, D, E, and F in order.
26. Run at least 3 replicates of your two most interesting filters (e.g., HEPA and the improvised filter that performed best).
27. Record all raw data directly onto the data sheet as it is collected. Do not transcribe from memory later.
28. At the end of the session: seal simulant container, bag and label spent filters, wipe down all surfaces with a damp towel. Remove PPE in order: gloves last.

Session 3 — Analysis and Reporting (90 min)

29. Enter all raw data into your group spreadsheet.
30. Calculate filtration efficiency for each filter using the appropriate formula (Section 5).
31. Calculate cost-per-percent-efficiency for each filter: divide filter cost by efficiency percentage.
32. Create a bar graph of filtration efficiency by filter type (x-axis: filter label; y-axis: efficiency %).
33. Create a second graph: cost (y-axis) vs. efficiency (x-axis) as a scatter plot to visualize the value tradeoff.
34. If using Tier 2: also create a time-series line graph of upstream vs. downstream PM2.5 concentration for your best filter.
35. Complete the Discussion Questions on the student data sheet.
36. Prepare your group presentation or lab report per the instructor's format.

7. Student Data Sheet

Complete all fields in pen during the lab. Do not erase — draw a single line through errors and initial.

Group Information

Group Members:	**Date:**	**Aerosolization Method Used:** A — Fluidized Bed B — Impulse Injection

Simulant Used:	**Flow Rate (L/min):**	**Measurement Tier Used:** Tier 2 — Optical Sensor Tier 3 — Gravimetric

Pre-Lab: Hypothesis and Predictions

Your hypothesis (If/Then/Because):

Which filter do you predict will perform BEST and why?	**Which improvised filter (E or F) do you think will outperform the other?**

Setup Observations

Calibrated pump flow rate: __________ L/min	**Simulant mass per run (Method B) / bed load (Method A):** __________ g

Describe the simulant's behavior during aerosolization (color, movement, visibility in chamber):

Data Table 1 — Tier 2 Optical Sensor Results (PM2.5)

Complete only if using Tier 2. Record mean concentrations from the full run for each filter.

Filter	Label	Mean Upstream PM2.5 (µg/m³)	Mean Downstream PM2.5 (µg/m³)	Efficiency (%)	Replicate #
Control (none)					1
HEPA — Filter A					1
MERV-13 — Filter B					1
MERV-8 — Filter C					1
Surgical mask — Filter D					1
Cotton — Filter E					1
Coffee filter — Filter F					1
HEPA — Filter A (rep 2)					2
HEPA — Filter A (rep 3)					2
Best improvised (rep 2)					2
Best improvised (rep 3)					2

Yellow rows = replicate trials. Calculate mean efficiency across all replicates for your top filters.

Data Table 2 — Tier 3 Gravimetric Results

Complete only if using Tier 3. Record membrane masses to 4 decimal places.

Filter	Membrane ID	Tare Mass (g)	Post-Exp Mass (g)	Mass Collected (mg)	Efficiency (%)	Rep #
Control	↑ UP					1
Control	↓ DOWN				← *calculate*	1
Filter A	↑ UP					1
Filter A	↓ DOWN				← *calculate*	1
Filter B	↑ UP					1
Filter B	↓ DOWN				← *calculate*	1
Filter C	↑ UP					1
Filter C	↓ DOWN				← *calculate*	1
Filter D	↑ UP					1

Filter D	↓ DOWN				← *calculate*	1
Filter E	↑ UP					1
Filter E	↓ DOWN				← *calculate*	1
Filter F	↑ UP					1
Filter F	↓ DOWN				← *calculate*	1

Data Table 3 — Cost vs. Efficiency Summary

Complete after calculating all efficiencies. Use this table to build your scatter plot.

Filter	Material	Cost per Filter ($)	Efficiency (%)	Cost / 1% Efficiency ($)
A				
B				
C				
D				
E				
F				
Control				

Graph Space — Filtration Efficiency Bar Chart

Draw your bar chart here, or tape/staple a printed graph from your spreadsheet.

Y-axis: Filtration Efficiency (%) *X-axis: Filter Type (A–F, Control)*

Discussion Questions

Answer all questions in complete sentences. Use your data to support every claim.

1. **Which filter had the highest filtration efficiency? Was this what you predicted? Explain why or why not based on what you know about how that filter works.**

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2. **Compare the efficiency of Filter E (cotton) and Filter F (coffee filter) to the commercial MERV-8 filter (Filter C). What does this tell you about improvised filtration materials for use in an emergency lunar habitat?**

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3. **Look at your cost-per-efficiency table. Which filter offers the best value? Which offers the worst? What engineering tradeoffs does a mission planner have to consider when choosing between them?**

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4. **NASA requires HEPA filtration (99.97% at 0.3 μm) for lunar cabin air. Did your HEPA filter sample reach that standard? If not, propose at least one design change to your experiment or the filter setup that could improve performance.**

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5. **Describe one source of experimental error in your procedure. How could this error have affected your efficiency calculation — would it make the result too high or too low? How would you fix it in a repeated study?**

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6. **Real lunar dust particles are electrostatically charged, which makes them cling to surfaces more aggressively than Earth dust. How might this property affect the filtration efficiency results you measured, and what additional filter design features might address it?**

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7. **If you were designing the air filtration system for a 6-person lunar base expected to operate for 2 years, which filter type or combination would you recommend, and why? Consider efficiency, cost, availability, and replaceability.**

Post-Lab Reflection

What is the most surprising thing you learned from this experiment?

If you were an astronaut on the Moon and your HEPA filter failed, what would you do?

8. Extension Activities

For groups that finish early or want to go deeper:

- Repeat the experiment with the simulant sieved to < 10 μm only (respirable fraction). Does efficiency change for smaller particles?
- Test filter efficiency after 3 repeated uses. Does a clogged filter perform better or worse? Why?
- Research HEPA filter design: how do glass fiber mats trap particles by inertial impaction, diffusion, and interception? Draw a diagram.
- Connect to real mission design: look up the life support specifications for the Artemis lunar Gateway. What filtration standards does NASA specify? How does your best filter compare?
- Economic extension: calculate how many filter replacements would be needed per year in a 6-person habitat at your measured loading rate. What would that cost?
- Graphing extension: plot a particle capture efficiency curve for a HEPA filter (efficiency vs. particle size from 0.1 to 10 μm) using published manufacturer data. Overlay your measured data points.

9. References and Further Reading

- NASA Human Research Program — Lunar Dust Toxicity Report (2014): humanresearchroadmap.nasa.gov
- Exolith Lab lunar simulants — ordering and specs: exolithlab.com
- NASA Dust Mitigation Gap Assessment Report (2016): globalspaceexploration.org
- Plantower PMS5003 datasheet and Arduino library: github.com/fu-hsi/pms
- NASA BIG Idea Challenge 2021 — student lunar dust mitigation projects: nasa.gov/bigidea
- ESA — The Toxic Side of the Moon: esa.int/Science_Exploration/Human_and_Robotic_Exploration