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Multi-criteria trade-off analysis of dry particle size classification technologies for lunar regolith processing

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Abstract

Renewed interest in long-duration lunar exploration has driven the development of in-situ resource utilisation technologies to reduce reliance on Earth-supplied materials. Effective particle size classification of lunar regolith is one of the critical beneficiation steps for the selective preparation of feedstock to improve the performance of downstream extraction and utilisation systems. Fluid-based classification methods, that are generally used for terrestrial applications, are unsuitable for the lunar environment making dry processing technologies the only viable approach. Building on prior experimental campaigns that have established the feasibility and performance characteristics of a range of dry particle size classification technologies, this study presents a systematic trade-off analysis to comparatively evaluate and rank competing approaches under a unified multi-criteria framework. This framework consists of 13 evaluation parameters weighted to reflect the operational priorities of lunar regolith processing. A one-at-a-time sensitivity analysis across 26 perturbation scenarios was conducted to assess the robustness of the ranking outcomes. The Rotary Sieve (RS) was identified as the most promising technology, achieving the highest weighted aggregate score and retaining the top rank across all evaluated scenarios, demonstrating the robustness of this outcome to variations in the assigned parameter weights. The multi-criteria evaluation framework developed in this study serves as a living reference instrument for dry particle size classification technology selection, providing a transparent and updatable basis for future assessments as experimental data and higher-fidelity operational information become available, supporting the long-term technology maturation roadmap for lunar ISRU architectures.

Keywords: ISRU; Space mining; Moon; Lunar regolith processing; Particle size classification

1. Introduction

Sustained lunar exploration and long-term surface operations require the utilization of locally available resources to reduce dependence on Earth-supplied materials (Zhang et al., 2023). Lunar in-situ resource utilization (ISRU) is therefore regarded as a critical enabler of future lunar architectures (Gerald et al., 2013; Heiken et al., 1991). Lunar regolith, an unconsolidated surface layer comprising a heterogeneous mixture of mineral and rock fragments, breccias, glasses, and agglutinates spanning a wide range of particle sizes and compositions constitutes the most abundant and accessible natural resource on the Moon (Heiken et al., 1991). Owing to its mineralogical content, regolith has been identified as the primary feedstock for ISRU technologies, including oxygen production, metal extraction, and construction material manufacturing, thereby enabling essential surface infrastructure such as landing pads and habitats (Crawford, 2015; Meurisse et al., 2018; Lomax et al., 2020; Sargeant et al., 2021; Guerrero-Gonzalez and Zabel, 2023; Xu et al., 2025). These capabilities are fundamental to sustainable, long-duration lunar exploration; however, resource extraction

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represents the downstream stage of a broader processing chain. Before regolith can be reliably converted into usable products, preliminary treatment steps that are collectively referred to as beneficiation, must be undertaken to prepare and refine the raw material for subsequent utilization (Hadler et al., 2020).

However, beneficiation of lunar regolith is far from straightforward due to the material's intrinsic mineralogical heterogeneity, complex particle morphology, and broad particle size distribution, ranging from sub-micron dust to millimetre-scale grains (Qin et al., 2025). The regolith particles are typically angular, irregular, and highly abrasive, with pronounced interparticle cohesion in the fine fractions (Turyshev, 2025). Electrostatic charging, promoted by vacuum exposure and solar radiation, further influences particle behaviour and flow characteristics (Mazumder et al., 2010). These material-specific challenges are compounded by the lunar environmental conditions, including reduced gravity, the absence of atmosphere, extreme temperature fluctuations, and stringent mass and energy constraints, which limit the direct application of terrestrial beneficiation technologies. These challenges necessitate a structured and staged approach to lunar regolith processing, where individual unit operations are tailored to operate reliably under these constraints (Rasera et al., 2020). Broadly, the beneficiation of lunar regolith can be divided into two primary functional stages: particle size classification and mineral enrichment. In the former, the feedstock is refined according to a defined size distribution, thereby improving material handling, process stability, and reaction efficiency in subsequent steps, while the latter seeks to increase the concentration of specific target minerals through various separation mechanisms (Rasera et al., 2020; Kulkarni and Franke, 2024).

The importance of controlled particle size distribution (PSD) is underscored by the requirements of downstream lunar ISRU processes. For example regolith based additive manufacturing approaches, require fine regolith dust to ensure that individual particles remain smaller than the printing layer height, thereby preventing structural defects (Altun et al., 2021). Similarly, selective laser melting experiments for regolith simulants have employed pre-sieved feedstocks to promote uniform energy absorption within the powder bed (Fateri and Gebhardt, 2015). Other processes for oxygen extraction using molten salt electrolysis that use porous cathode cups, require particle sizes compatible with the cathode containment meshes to avoid the loss of fine dust into the electrolyte solution (Lomax et al. 2020; Seidel et al., 2025). Hydrogen reduction experiments with ilmenite, in which hydrogen reacts with ilmenite at high temperatures to produce water that is subsequently electrolysed to yield oxygen, have also been conducted using controlled grain size fractions for ilmenite, with Apollo sample findings indicating that ilmenite concentrations in lunar mare regions are highest within particle fractions below 250 μm (Sargeant et al., 2020; Heiken et al., 1991). Moreover, regolith-based concrete formulations favour the use of fine particles to enhance mechanical properties (Sik Lee et al., 2015). Collectively, these studies demonstrate that particle size classification is not an isolated processing step but a cross-cutting requirement influencing the performance, efficiency, and durability of multiple regolith utilization technologies.

Size separation of regolith particles has been largely overlooked, however most reduction processes have yet to be optimised with respect to particle size (Rasera et al., 2020).

The lunar regolith particles have a characteristic angular shape that makes them highly abrasive with a mean particle size smaller than 100 μm (Rasera et al., 2020; Rasera et al., 2025). In terrestrial mining industry, size classification of fine particles (< 200 μm) generally implements wet processing methods for improving processing efficiency and throughput (Wills and Finch, 2016a). This is however not possible for lunar applications, and therefore innovative dry processing methods need to be implemented. A number of dry particle size classification technologies have been experimentally investigated for lunar regolith applications, employing diverse physical principles ranging from mechanical screening to electrostatic transport (Zhao et al., 2026).

The selection of a particle size classification technology extends beyond the unit operation itself, as the performance parameters of the classifier directly constrain the design and efficiency of both upstream material handling systems and downstream extraction processes, highlighting its integrative role within the overall processing chain. Moreover, the internal operational performance of a particle size classification system is itself governed by multiple interdependent and often competing parameters, where improvements in one metric can often lead to penalties in another. For instance, while prolonged operation of a vibratory sieve may increase separation efficiency, it simultaneously increases processing time and energy consumption. Consequently, the selection of an appropriate separator for lunar implementation requires a structured trade-off analysis to balance competing performance objectives and system constraints.

Although individual dry particle size classification technologies have been experimentally validated, no structured framework has been implemented to comparatively evaluate competing technologies under a unified set of criteria reflective of the lunar operational environment. The absence of such a framework leaves technology selection without a transparent, quantitative, and reproducible basis, and limits the ability to assess how robust technology rankings are to the uncertainties inherent in early-stage experimental data. To address this gap, this study has developed and applied a multi-criteria trade-off analysis framework comprising 13 evaluation parameters specifically formulated to capture technical performance as well as lunar operational constraints. The framework is applied to seven candidate dry particle size classification technologies that have already been experimentally validated. A one-at-a-time sensitivity analysis is also conducted to quantify the robustness of the ranking outcomes to variations in parameter weights. While the analysis identifies the most promising technology based on currently available experimental evidence and state of knowledge, the evaluation framework is structured to accommodate future updates as new research data becomes available, ensuring its continued relevance as a decision support instrument for technology maturation and selection for future lunar ISRU processing architectures.

2. Methods

This section outlines the methodology used to evaluate and compare particle size classification technologies for the processing of lunar regolith. A structured literature review was conducted to identify and characterise relevant classification methods and their operational principles. Building on this, a trade-off analysis framework was developed to assess the performance of each technology against key evaluation parameters. Within this framework, a sensitivity analysis was also performed to examine the robustness of the results from the trade-off analysis.

2.1. Literature review

A structured literature review was conducted as the primary method for identifying and characterising dry particle size classification technologies applicable to lunar regolith processing. Scientific journal articles, conference proceedings, technical reports, and space agency publications were systematically screened to identify technologies that have been specifically developed for, or experimentally validated under, space-relevant conditions, including vacuum environments, reduced gravity, or regolith simulant testing. Technologies relying on wet or fluid-based processing principles were excluded, reflecting the operational constraints of the lunar surface environment.

2.2. Trade-off analysis

Following the literature review, relevant technical and operational information was systematically compiled and evaluation parameters for the trade-off analysis were defined. Parameter selection was informed by available state-of-the-art knowledge and the specific operational requirements of the lunar environment. A structured scoring framework was subsequently developed for the assessment of each technology against the defined criteria. The Analytical Hierarchy Process (AHP) was used to derive weights for the evaluation parameters. A hierarchically structured AHP was implemented, wherein parameters were grouped into thematic categories and pairwise comparison matrices were constructed at both category and parameter levels. This was done to reduce the analytical load and limit the number of matrices required. Consistency ratios were then calculated for all matrices and iteratively refined where necessary to satisfy the accepted threshold. The alternative technologies under consideration were scored according to the defined scoring framework and the AHP-derived parameter weights were used to get the normalized scores for each technology.

A one-at-a-time sensitivity analysis was then conducted to assess the robustness of the AHP-derived weighting structure and the stability of the trade-off analysis results. Each parameter weight was systematically varied by ±10 % relative to its baseline value, reflecting plausible uncertainty in expert judgment and consistent with established practice in multi-criteria decision-making (MCDM). Following each variation, the remaining weights were proportionally renormalised to preserve their relative proportions and maintain the total weight sum, ensuring mathematical consistency throughout. The results from this analysis were evaluated to determine the stability of the preferred solution and to validate the technology selection for further maturation and testing.

Additionally, to further complement the sensitivity analysis for assessing robustness of the AHP-derived weighting structure, an independent expert elicitation exercise was conducted. Five experts in related research fields were asked to conduct pairwise comparisons of the evaluation parameters through a structured questionnaire using Saaty's scale of relative importance. The questionnaire included only the evaluation parameters and their respective descriptions, without references to any specific particle size classification technologies or expected trade-off outcomes, to mitigate technology-related bias. The sequence of comparisons was randomized to reduce ordering effects and promote independent judgement. Following data collection, pairwise comparison matrices were reconstructed, consistency ratios were evaluated, and expert judgements were aggregated using the geometric mean approach to derive an expert-informed weighting structure for comparison with the baseline weighting framework. While the initial sensitivity analysis evaluated the stability of the trade-off results under systematic variation of the weighting factors, the expert elicitation exercise provided an independent assessment of the weighting priorities and reduced reliance on a single-author judgement framework.

3. Particle size classification systems

This section provides an overview of the particle size classification technologies considered in this study. Seven candidate systems were selected based on their relevance to lunar regolith processing and their representation in the existing literature. Each technology is briefly described in terms of its operating principle, typical performance characteristics, experimental results and potential applicability under lunar environmental conditions.

3.1. Rotating Cone Separator

The Rotating Cone Separator (RCS) was developed by Berggren et al. (2011) as part of the Lunar Soil Particle Separator (LSPS) concept. In this separator, classification is achieved by feeding soil uniformly onto a rotating, textured cone near its apex, from which particles cascade outward toward the perimeter as shown in Fig. 1. The trajectories of the particles depend on their surface area-to-mass ratio which is directly related to the particle size. Therefore, the finer particles experience greater frictional resistance and slower radial acceleration, while coarser grains roll and bounce outward more rapidly thereby resulting into the classification of particles. Cone geometry and rotational speed can be selected such that complete particle removal is achieved within a single revolution. This mesh-free operating principle inherently eliminates screen-blinding issues associated with conventional sieving. Laboratory experiments were conducted using JSC-1A and NU-LHT-2 M lunar regolith simulants, with feed material pre-sieved to remove particles larger than 1 mm.

The initial phase of experiments was conducted with an aluminium cone of 30°cone angle, 15 cm cone diameter, tested at 40–250 rpm rotational speeds with 15 g min^{-1} feed rate. The next phase of the system with a scaled-up apparatus was conducted with input feed rate of about 333 g min^{-1}. In this system the cone diameter was 43 cm, different cone angles were tested (20°, 30° and 40°) with construction paper as the cone surface. Upon experimental testing, optimal performance of the system was observed with a 30° cone angle with the vertical axis of the cone inclined by 10° and rotational speeds of about 80–140 rpm. Upon evaluation of results from these experiments, a two-stage configuration was demonstrated to produce three distinct size fractions: coarse, medium and fine. Testing under vacuum (~0.7 torr) and ambient conditions yielded comparable classification grades; however, vacuum conditions produced approximately 25 % less fine fraction mass, suggesting that the absence of interstitial air influences fine particle transport along the cone surface. The mesh-free design and mechanically simple actuation are advantageous for lunar deployment; however, the reduced fine fraction yield under vacuum and unvalidated performance under lunar gravity as of the current evidence represent limitations requiring further investigation before operational maturation of the system.

3.2. Slotted Ramp Separator

The Slotted Ramp Separator (SRS), also developed by Berggren et al. (2011) as part of the LSPS concept, achieves classification by feeding soil onto an inclined, vibrating surface (ramp) fitted with slots at fixed intervals along its length. The classification in an SRS system relies on surface area-to-mass ratio of particles: finer particles experience greater frictional resistance given their higher surface area-to-mass ratio, causing them to decelerate and fall through the slots progressively along the ramp, while coarser particles continue rolling toward the base. Key operational parameters for the system include ramp angle, ramp length, slot gap, and surface roughness, each of which directly influences separation performance. Laboratory experiments were conducted using JSC-1A and NU-LHT-2M simulants with the experimental setup as illustrated in Fig. 2. The vacuum experiments were conducted at a ramp angle of 45° using two slot gap configurations (0.17 cm and 1.3 cm). With a feed containing approximately 35–40 % fines (<75 μm), only 1.5 % fines were retained in the coarse product. High-quality fine product was achieved with the 0.17 cm slot gap under vacuum conditions, demonstrating that relative friction rather than air resistance constitutes the primary separation mechanism. High-frequency vibration was found to significantly aid particle flow and dispersion across the ramp surface. The SRS demonstrates effective fine-coarse separation with minimal cross-contamination. A sequential configuration with progressively increasing slot gaps (0.17 to 1.9 cm) is under investigation to broaden the achievable classification range for tailored downstream ISRU feedstock production.

3.3. Electrostatic Travelling Wave

The Electrostatic Travelling Wave (ETW) classifier achieves size-based separation by exploiting differences in charge-to-mass ratio between particle size fractions. Under a spatially varying electric field, fine particles attain sufficiently high charge such that the upward electrostatic force exceeds gravitational attraction, while coarser grains

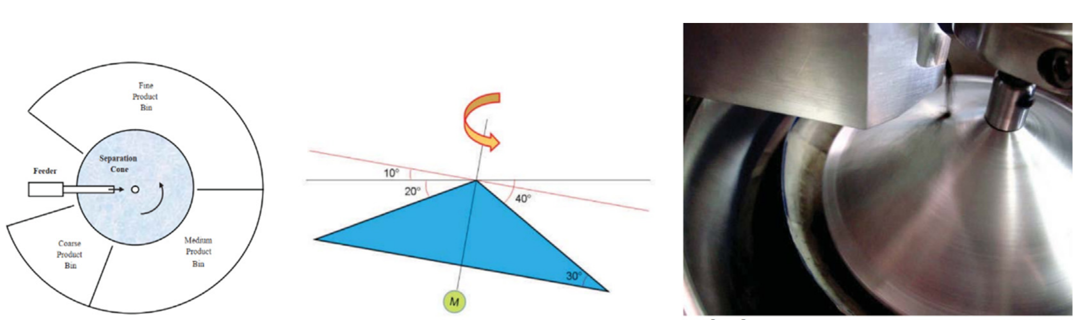

Fig. 1. (a) Conical separator schematic top and side views; (b) rotating Cone Separation hardware test (Berggren et al., 2011).

Fig. 2. Slotted Ramp Separator (SRS). Left: final assembly for testing; Right: Vacuum chamber in preparation for testing (Berggren et al., 2011).

remain on the conveyor (Kawamoto, 2008). This operating principle is entirely independent of mechanical agitation and mesh-based exclusion. Several ETW architectures have been progressively developed and experimentally validated. Kawamoto (2014) demonstrated two initial configurations using FJS-1 lunar regolith simulant an electrodynamic sieve with parallel enamel wire electrodes (Fig. 3), transporting sub-20 μm particles at yields below 1 %, and a filing separator with an L-shaped collector (Fig. 4) achieving yields exceeding 10 % under comparable conditions. Subsequent vacuum testing at approximately 1.5×10^{-2} Pa by Adachi et al. (2017) confirmed that reduced pressure increased particle charge density and levitation height, enabling efficient classification of particles smaller than 20 μm, with DEM simulations predicting that under lunar gravity, particles smaller than 10 μm could be captured at collector heights of approximately 1.5 m. Subsequent developments by Kawamoto (2025) expanded this approach into more architectures: an electrodynamic sieve (optimal frequency ~10 Hz, <1 % yield), a flying classifier using a four-phase high-voltage conveyor (classification peak ~15 μm, ~1 % yield at 1–2 kV), an agitating standing-wave classifier (~12 μm mean size, ~10 % yield), and a lifting travelling-wave classifier with integrated feeder (~12 μm product at ~30 % yield, the highest reported). The ETW approach is lightweight, low-power, and consumable-free, with performance characteristics that improve under lunar vacuum and reduced gravity conditions. However, yield limitations and scalability to operationally relevant ISRU throughputs remain the principal challenges for further development (Kawamoto, 2025).

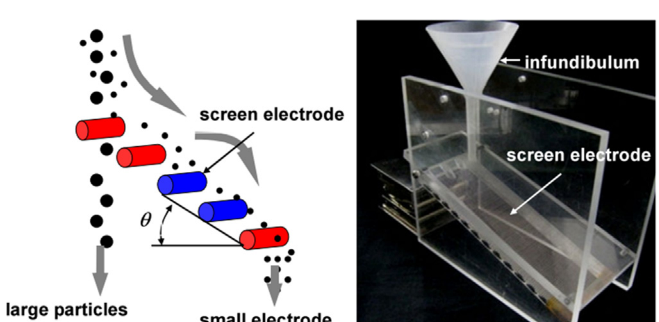

Fig. 3. Electrostatic sieve-type particle size classification system (Kawamoto, 2014).

3.4. Lunar Excavation and Size Separation System

The Lunar Excavation and Size Separation System (LES^3) is a lightweight mechanism (<2 kg) developed for the LUVMI-X rover, integrating regolith acquisition and particle size classification within a single unit (Just et al., 2022). The system comprises a cylindrical inlet, a robotic arm, and a base, each actuated by high-torque stepper motors as shown in Fig. 5. Classification is performed through two mesh plates housed within the inlet: a coarse mesh for pre-separation of large fragments and a fine mesh through which the target fine fraction is directed to a dedicated storage container. Spring-loaded gates, actuated by cam profiles, control the discharge of each size fraction into separate collection paths. An optional cleaning cycle, in which the vibration motor is reactivated with the arm tilted downward, is incorporated to dislodge material retained on the mesh surfaces. The dry sieving experiments used four lunar regolith analogue materials: UoM B which is a complex ferro silicate, two regolith simulants TUBS M and TUBS T, and a pumice powder (Hess Pumice Grade 1/0). These tests showed that with apertures ≥500 μm the system passes >99 % of the material in a short residence time (≈ 40–250 s for 200 g batches), but efficiency drops to ~75 % and times increase to several thousand seconds as the aperture is reduced to 250 μm. Residence time follows a power law with aperture size, so finer screens dramatically lengthen processing, a problem mitigated by keeping batch masses low (≈ 200 g) or using a larger sieve area, and by employing two orthogonal vibration motors which cut the required time by roughly 45 % for larger apertures and 20–35 % for finer ones. In the integrated prototype, LES^3 successfully produced two distinct fractions (coarse > 500 μm, fine < 500 μm) from up to 100 g of regolith per scoop with material loss of only

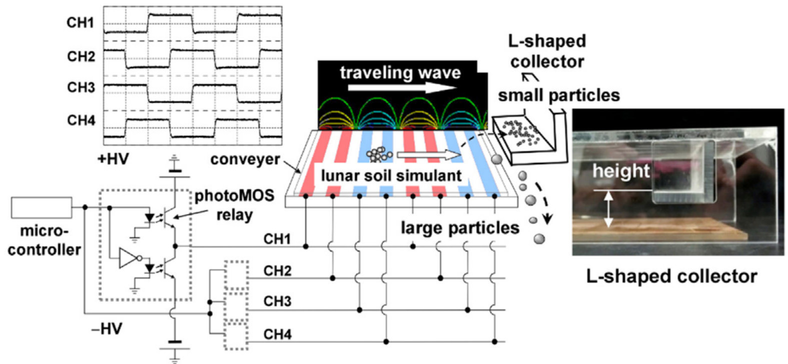

Fig. 4. Electrostatic filing-type particle size classification system (Kawamoto, 2014).

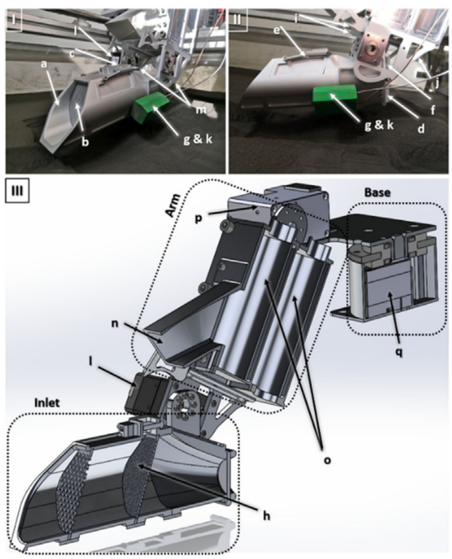

Fig. 5. Mechanical design of the described prototype. Features I and II show the inlet with all its components in a laboratory environment and feature III presents a sliced 3D rendering of the whole mechanism with an indication of the three main parts (Just et al., 2022).

3–4 %. The integration of excavation and classification into a single low-mass unit represents a significant system-level advantage for rover-based ISRU operations. However, the dual-screen configuration is prone to blinding of the mesh, and classification performance under vacuum and reduced gravity conditions remains to be independently validated.

3.5. Vibrational segregation using Brazil Nut Effect

Vibrational size classification based on the Brazil Nut Effect (BNE) exploits vibration-induced granular segregation; wherein repeated mechanical agitation causes larger particles to migrate upward through a particle bed while finer particles settle toward the base (Rasera et al., 2025; Kawamoto, 2025). Segregation is governed by a combination of void filling, convective flow, buoyancy, and arching mechanisms, with the relative contribution of each dependent on vibration frequency, amplitude, and ambient pressure conditions (Rasera et al., 2025). The researchers investigated vibration-induced segregation in sealed vials containing Apollo 15 regolith (A15601) and three simulants (JSC-1, LMS-1, TUBS-M), subjected to vibration at 15–70 Hz. Micro-CT imaging of A15601 revealed a stable three-layer structure comprising a coarse upper layer, compacted middle layer, and fine base, which intensified with increasing vibration frequency (Rasera et al., 2025). Among the simulants, TUBS-M reproduced A15601 behaviour most closely, whilst JSC-1 exhibited efficient segregation but divergent structural organization. This work validated the theory for vibrational classification of lunar regolith.

A prototype vibratory classifier based on the same fundamental principle was developed and investigated experimentally by Kawamoto (2025), utilizing an inclined tube driven by piezoelectric actuation at approximately 8 g and 150 Hz, amplified through a rhomboid frame as shown in Fig. 6. Larger grains migrated upward and were expelled down the incline, whilst finer particles were transported upward through the tube. Classification cut size was controlled through inclination angle, with angles of approximately 30° preferentially conveying particles smaller than 100 μm. Continuous processing rates of several tens of kilograms per hour were demonstrated without consumables. The BNE classifier operates without meshes or fluid media and demonstrates compatibility with vacuum conditions; however, precise cut size control and performance under lunar gravity require further validation.

3.6. Centrifugal Sieve

The Centrifugal Sieve (CS) achieves size classification by using centrifugal force as the primary driver of particle-screen interaction, supplemented by a gentle shearing flow and vibratory motion (Walton et al., 2015; Dreyer et al., 2012). Material enters a rotating cylindrical screen, within which an internal helix rotates at a slightly higher speed to shear the particle bed and convey material axially as shown in the Fig. 7. Natural stratification of the granular bed, driven by the Brazil Nut Effect, positions finer particles preferentially at the screen surface, where centrifugal acceleration drives them through the screen pores. Coarser

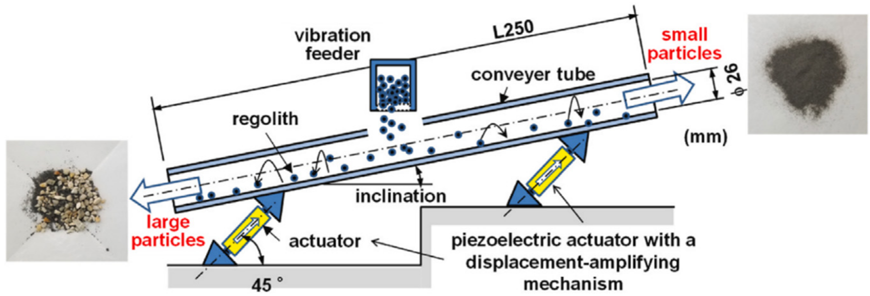

Fig. 6. Vibrational classification system (Kawamoto, 2025).

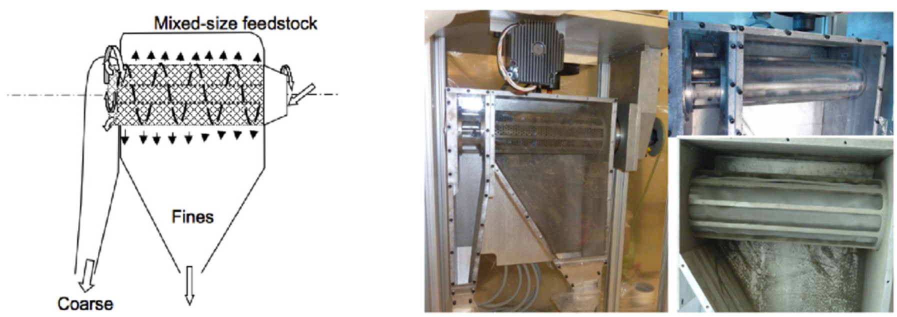

Fig. 7. (a) Schematic of centrifugal sieve concept. (b) Ground test setup for centrifugal sieve; Left: 4.6 mm screen. Right: during and post testing images with 100 µm screen (Dreyer et al., 2012).

particles are conveyed axially to a separate downstream outlet. Microgravity flight-tests hardware utilising a 100 µm screen was operated at 188 rpm (screen) and 248 rpm (auger), generating a centrifugal acceleration of approximately 1.5 g at the screen wall. Under these conditions, JSC-1A simulant was classified into two fractions at the 100 µm cut size, achieving approximately 50 % mass split between fine and coarse outlets. Rapid residence times, continuous feed capability, and effective scalping performance were demonstrated. The gravity-independent operating principle of the CS represents its most significant advantage for space resource applications. Scalability and long-duration mesh integrity under abrasive regolith conditions remain to be validated.

3.7. Rotary Sieve

The Rotary Sieve (RS), commonly referred to as a trommel, is among one of the oldest screening devices in mineral processing (Wills and Finch, 2016b). It consists of a slightly inclined, rotating cylindrical screen through which undersized particles pass while oversize material is conveyed axially toward the outlet. Particle motion within the drum is governed by rotational speed, with three distinct flow regimes identifiable as speed increases as shown in the Fig. 8. At low speeds, particles are carried slightly up the drum wall before cascading back down in a slumping motion (Fig. 8.a). At moderate speeds, particles travel higher along the circumference before falling in a cataracting motion, which is associated with optimal screening efficiency (Fig. 8.b. At excessive speeds, centrifugal forces cause particles to adhere to the drum wall, suppressing particle-screen interaction and reducing classification performance (Fig. 8.c). Cataracting motion is associated with optimal screening efficiency, whereas centrifuging, causes particles to adhere to the drum wall and reduces throughput. Chen et al. (2010) identified the optimal operating window for a laboratory trommel handling silica sand as 360 g min^{-1} feed rate, 43 rpm, and 5° inclination, achieving approximately 90 % screening efficiency for the undersized fraction. Efficiency was observed to decline at inclinations beyond 5° and at rotational speeds outside the cataracting regime.

A rotary sieve with concentric sieves of different mesh sizes was previously investigated by Chepil (1962) to support compact on-site testing and analysis. The developed system is shown in Fig. 9. The Beneficiation of Regolith and Mobile Excavation (BREMEN) project by Zhao et al. (2025) advanced this concept incorporating inner (500 µm) and outer (100 µm) mesh screens, capable of producing three simultaneous size fractions: greater than 500 µm, 500–100 µm, and less than 100 µm. A mechanical agitation mechanism was implemented to mitigate sieve blinding during extended operation. Hardware testing with a total of 18 kg of EAC-1A lunar simulant yielded screening efficiencies of approximately ~77 % for the intermediate fraction, ~75 % for the fine fraction, and ~60 % for the coarse fraction.[1] The dual-concentric configuration

[1] The reported values are taken from the evaluation report for Team BREMEN after the completion of ESA's 2nd Space Resources Challenge.

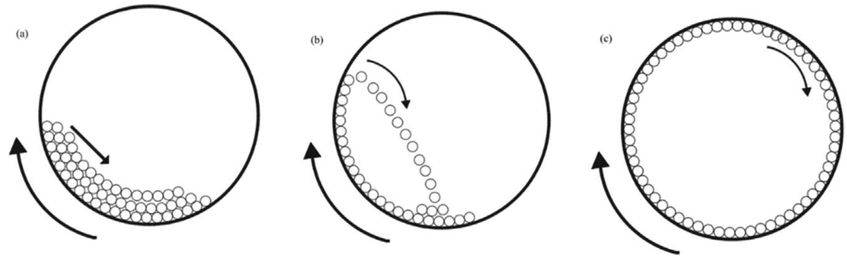

Fig. 8. Forms of particulate motion in rotating cylinders: (a) slumping; (b) cataracting; (c) centrifuging (Chen et al., 2010).

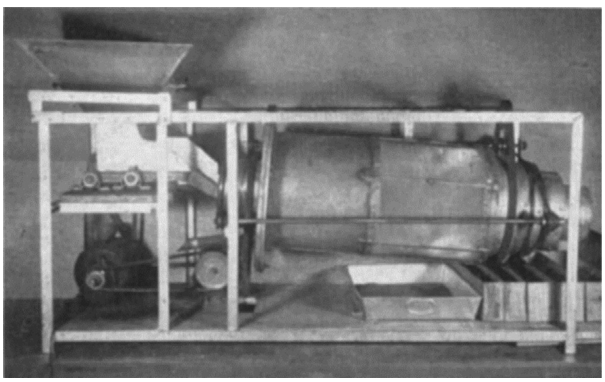

Fig. 9. A compact rotary sieve ready to use (Chepil, 1962).

represents a meaningful advancement in classification resolution for lunar applications; however, the comparatively lower coarse fraction efficiency and long-term mesh integrity under abrasive regolith conditions warrant further investigation.

4. Trade-off analysis

This section describes the framework used to evaluate and compare the selected particle size classification technologies. The evaluation parameters considered in the analysis are first defined, followed by the development of a scoring framework to quantify the performance of each technology. The relative importance of the parameters is then determined using the Analytic Hierarchy Process (AHP). The resulting weights and scores are combined to perform the trade-off analysis and rank the candidate systems. Finally, a sensitivity analysis is conducted to assess the robustness of the rankings to variations in the assigned parameter weights.

4.1. Evaluation parameters

The evaluation parameters selected for the trade-off analysis are summarised in Table 1. Parameter selection was guided by the operational constraints of the lunar surface environment, the performance requirements of regolith beneficiation processes, and the available quantitative and qualitative information for each candidate technology. Each parameter reflects a critical technical, operational, or programmatic consideration relevant to system feasibility and lunar mission integration.

4.2. Scoring framework

A discrete three-level scoring scale (10, 30, and 50) was adopted to evaluate each technology against the defined parameters. The scale represents low (10), moderate (30), and high (50) performance relative to the specific criterion. This structured scoring approach was selected to ensure clear differentiation between technologies while avoiding over-interpretation of minor performance differences that cannot be justified by available data. The use of a limited number of well-separated score levels enhance consistency in comparative assessment and improves transparency in the trade-off process. The discrete scale is particularly suitable for early-phase system evaluation, where performance data are often heterogeneous in quality and precision. The Table 2 gives more detail on the scoring framework used for each evaluation parameter.

4.3. Analytical hierarchy process (AHP) for allocation of weights to the evaluation parameters

A hierarchically structured AHP was employed to derive relative weights for the 13 evaluation parameters. Parameters were grouped into five thematic categories to reduce matrix dimensions to a manageable scale and improve consistency in pairwise comparisons. The categories were Separation Effectiveness, Operational Compatibility, System Robustness and Maturity, Scalability and Throughput, and Resource Requirements. The hierarchical structure for AHP is illustrated in Fig. 10.

Pairwise comparisons were conducted at both category and parameter levels using the Saaty's scale of relative importance (Saaty, 2008). Consistency ratios were calculated for all matrices and verified to remain below the accepted threshold of 0.1. Where this threshold was initially exceeded, pairwise judgements were iteratively revised until consistency was achieved. Global parameter weights were obtained by multiplying the local weight of each parameter by its respective category weight. The resulting weights are summarised in Table 3. The complete

Table 1
Parameters for trade-off analysis and their descriptions.

Parameter	Description
Separation performance	The ability of the separator to accurately separate/classify the target particle size fraction into the respective flow (%).
Particle size range capability	The smallest and largest particle size that the separator can handle (μm or mm).
De-dusting performance	The ability of the separator to remove fine particle fraction from the feed.
Scalping performance	The ability of the separator to remove coarse particle fraction from the feed.
Feed type	The type of processing for a system: Continuous or Batch.
Dust production	A qualitative evaluation of dust generation behaviour of a system and its ability to limit and/or contain dust dispersion during operation.
Processing time	The total time required to process a given amount of feed material.
Scalability	The ease with which the system can be scaled up to support a large-scale infrastructure.
Technology readiness level	The current technology readiness level of the system for use in a mission according to ISO 16290:2013
Lunar applicability	The ability of a system to perform under the lunar environmental constraints such as reduced gravity, vacuum environment and wide range of operating temperature.
Operational reliability	The ability of the system to maintain performance under prolonged operation in the lunar environment its susceptibility to mechanical failure or clogging
Maintenance requirements	The ease, frequency and simplicity with which a system can be inspected, cleaned, serviced or repaired to minimize downtime and logistical support.
Power/energy demand	A qualitative assessment of the total energy and/or electrical power required for the systems operations.

Table 2
Scoring framework for evaluation parameters.

Parameter	Score = 10	Score = 30	Score = 50
Separation performance	Less than 50 %	50–75 %	More than 75 %
Particle size range capability	Limited to very narrow range of particle sizes	Limited to moderately wide range	Capable of separating across a very broad range of particle sizes
De-dusting performance	Poor at de-dusting (significant fines remain in the product or process)	Moderately effective at de-dusting (some fines remain in the overflow)	Excellent at removing fines from the overflow
Scalping performance	Poor at scalping (allows significant coarse material to contaminate the product)	Moderately effective at scalping (some coarse material remains in the underflow)	Excellent at removing coarse particles from underflow
Feed type	Strictly batch processing requiring frequent stops	Hybrid or semi-continuous modes with manageable interruptions	Continuous processing, ideal for high volume operations
Dust production	High dust generation	Moderate dust generation	Minimal to no dust generation
Processing time	High processing time (limited overall throughput)	Moderate processing time (acceptable for the desired output feed rate)	Low processing time (High material throughput)
Scalability	Limited scalability (Difficult to adapt to increased production volumes)	Moderately scalable (with design changes or limitations)	Highly scalable to meet a wide range of production demands
TRL	TRL 1–3	TRL 4–6	TRL 7–9
Lunar applicability	Severe net negative impact of the lunar environment on system performance, requiring significant mitigation or redesign.	Moderate, low, or mixed impact of the lunar environment on performance; system remains functional with limited adaptation.	Negligible impact or net positive influence of the lunar environment on system performance, with conditions either not affecting or enhancing operation.
Operational reliability	Low	Moderate	High
Maintenance requirements	Difficult to maintain or requires frequent maintenance	Moderately maintainable (specialized tools or process might be necessary)	Low maintenance or easy to maintain (easy to inspect, clean, repair)
Power/energy demand	Very high	Moderate	Low

set of pairwise comparison matrices and individual consistency ratio values are provided in the supplementary material (S1_AHP Pairwise comparisons) for further information.

4.4. Trade-off analysis results

This section presents the results of the multi-criteria trade-off analysis. The evaluated technologies were scored according to the defined parameters, and the AHP-derived weights were applied to compute normalized weighted scores. The seven technologies are: Rotating Cone Separator (RCS), Slotted Ramp Separator (SRS), Electrostatic Travelling Wave based separation (ETW), Lunar Excavation and Size Separation System (LES3), Vibrational segregation using the Brazil Nut Effect (BNE), Centrifugal Sieve (CS), and Rotary Sieve (RS), as described in Section 3. The detailed evaluation matrix, including technology-specific performance indicators and the grading rationale for each parameter along with results

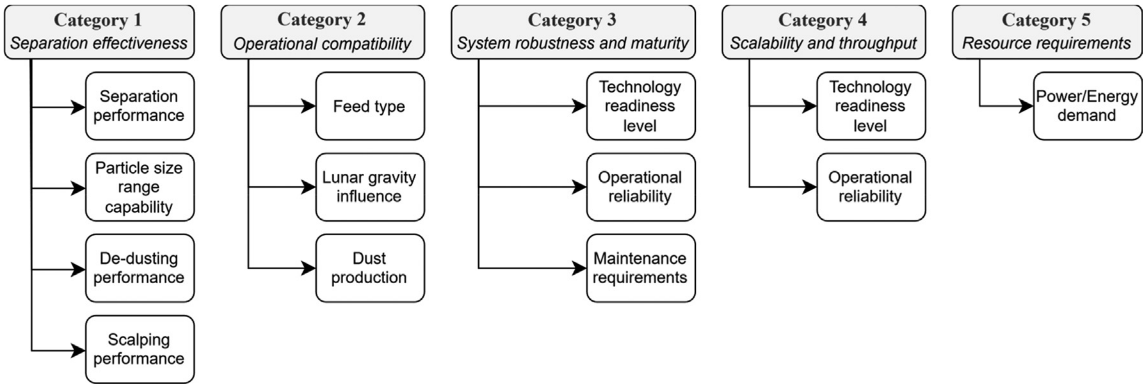

Fig. 10. Hierarchy for branched AHP to allocate weights for the evaluation metrics.

Table 3
Results of AHP with global weights of all evaluation parameters.

Category	Category weight	Parameter	Local weight	Global weight
Separation effectiveness	0.47	Separation performance	0.49	**0.23**
		Particle size range capability	0.29	**0.14**
		De-dusting performance	0.15	**0.07**
		Scalping performance	0.07	**0.03**
Operational compatibility	0.28	Feed type	0.26	**0.07**
		Lunar applicability	0.63	**0.18**
		Dust production	0.11	**0.03**
System robustness and maturity	0.11	TRL	0.09	**0.01**
		Operational reliability	0.67	**0.07**
		Maintenance requirements	0.24	**0.03**
Scalability and throughput	0.09	Scalability	0.25	**0.02**
		Processing time	0.75	**0.07**
Resource requirements	0.04	Power/energy demand	1.00	**0.04**

from the trade-off analysis, are provided in the supplementary material (S2_Evaluation matrix and S3_Trade-off results) and should be consulted alongside the results presented in this section.

Fig. 11 presents the trade-off analysis results in the form of a heatmap. The evaluation parameters are listed on the left along with their respective AHP-derived weights reflecting relative importance of each parameter. The dark red cells indicate the highest relative performance within a parameter row and dark blue cells indicate the lowest. Two important caveats apply to this colour scheme: a dark red cell in a low-weight parameter row does not carry the same absolute significance as in a high-weight parameter row, and parameters with very low weights (specifically TRL ($w = 0.01$) and Scalability ($w = 0.02$)) have low influence on the total score regardless of their colour appearance. The parameter must therefore be considered alongside the cell colours when drawing conclusions from the diagram.

The trade-off analysis reveals considerable variation in score margins between the seven technologies, and yet a clear separation emerges between the top three ranked solutions and the remaining alternatives. The margin between RS and CS is 4.63 %, while that between CS and SRS is only 2.15 %, indicating strong similarity in overall performance among these three technologies. In contrast, the margin between SRS and BNE rises sharply to 12.1 %, with subsequent margins averaging approximately 5–6 %, the only exception being the ETW – RCS pair, which exhibits a margin of just 1.32 %. The total weighted aggregate scores establish the overall ranking as follows: RS (38.90), CS (37.1), SRS (36.3), BNE (31.9), ETW (30.1), RCS (29.7), LES3 (27.9).

The three highest-weight parameters, namely separation performance, lunar applicability, and particle size range capability, collectively account for approximately 55 % of the total weighted score and therefore have a large influence on the final rankings. The top rank of RS is attributed to its high score in separation performance, its balanced performance across lunar applicability and particle size range capability, and its consistency across the remaining evaluation parameters. The second and third ranks of CS and SRS, respectively, similarly reflect balanced performance across most parameters; however, both technologies are outperformed by RS in dust production, operational reliability, and energy demand, as illustrated in the heatmap. A peculiar observation is the last-place ranking of LES3, which, despite achieving a high score in separation

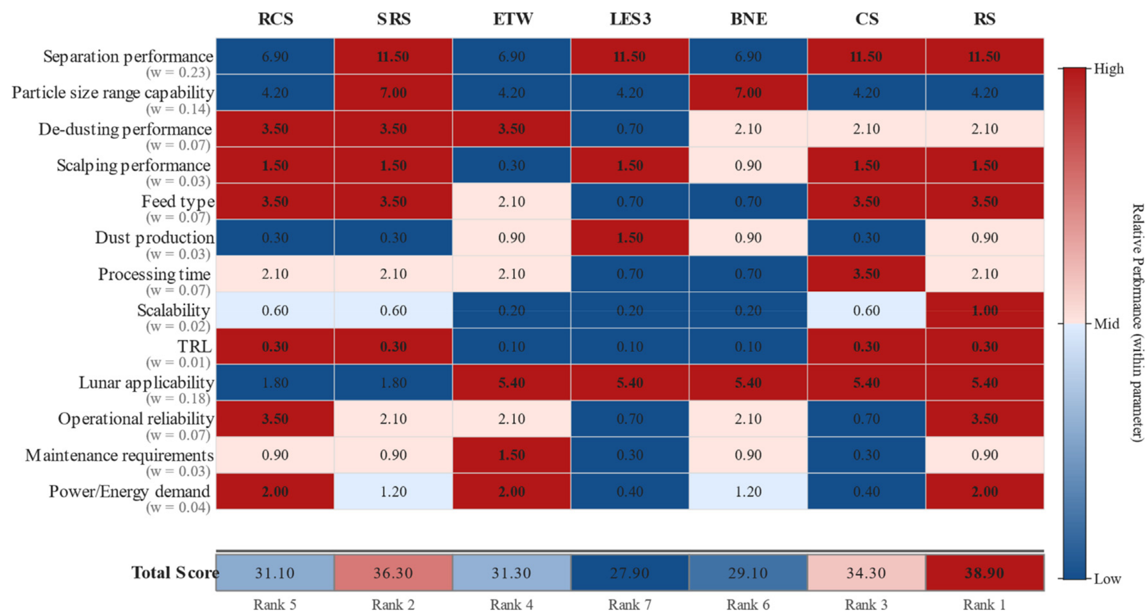

Fig. 11. Heatmap of the weighted evaluation scores for the seven dry particle size classification technologies across the 13 evaluation parameters. Cell values represent the weighted score for each technology-parameter combination. The total weighted aggregate score and the corresponding technology ranking are presented in the bottom row. Bold values indicate the highest score within each parameter row. Colour is normalised independently per row to reflect relative performance within each parameter.

performance, underperformed across the majority of the remaining parameters. This outcome is significant, as it demonstrates the ability of the evaluation framework to objectively differentiate between competing technologies that share a strong performance in a key parameter, thereby enabling informed selection among them. These results collectively highlight that while strong performance in high-weight parameters is necessary, consistent scores across the full parameter set are equally important for achieving a high trade-off ranking.

Overall, the results clearly establish RS as the leading technology among the seven candidates, and the heatmap provides an effective foundational framework for parameter-level technology comparison. The sensitivity of this ranking to variations in the AHP-derived parameter weights is examined in the following section.

4.5. Sensitivity analysis

A one-at-a-time sensitivity analysis was performed as per the methods described in Section 2.2. A total of 27 scenarios (26 + Baseline) were tested and the top ranked alternative, runner up alternative, scores for both and the score margin were evaluated. The evaluation matrices for each tested scenario along with the results for robustness are available in supplementary material (S4_One-at-a-time analysis and S5_Robustness results).

The results of the sensitivity analysis are presented in Fig. 12. The x-axis represents the deviation of the weighted aggregate score from each technology's baseline score, while the y-axis lists the seven technologies under evaluation. Each horizontal bar spans the full range of score deviations observed across all tested scenarios. The vertical dashed line at zero denotes the baseline reference, corresponding to the weighted aggregate score achieved by each technology under the original, unperturbed weight set (Baseline scenario). The total width of each bar, called the swing, is computed as the difference between the maximum and minimum score deviations from the baseline values observed across all scenarios and is annotated at the right end of the respective bar. The blue and red segments of each bar represent score deviations below and above the baseline, respectively. Technologies are arranged in descending order of swing from top to bottom, producing the characteristic tornado shape in which the gradient of sensitivity across the seven technologies can be observed.

The diagram reveals that LES3 and SRS exhibit the largest swing values of 1.316 and 1.158 respectively, indicating that their weighted aggregate scores are the most susceptible to changes in parameter weights across the tested scenarios. In contrast, BNE records the smallest swing of 0.604, identifying it as the most robust technology in terms of score stability.

The near-symmetry of the bars about the zero-deviation line indicates that the technologies are equally sensitive to increases and decreases in evaluation parameter weights, with no strong directional bias observed under the applied perturbation scheme.

RS retains the top rank across all 27 scenarios and exhibits a relatively low swing value of 0.656, confirming the robustness of this ranking outcome. CS and SRS consistently occupy the second and third ranks, respectively,

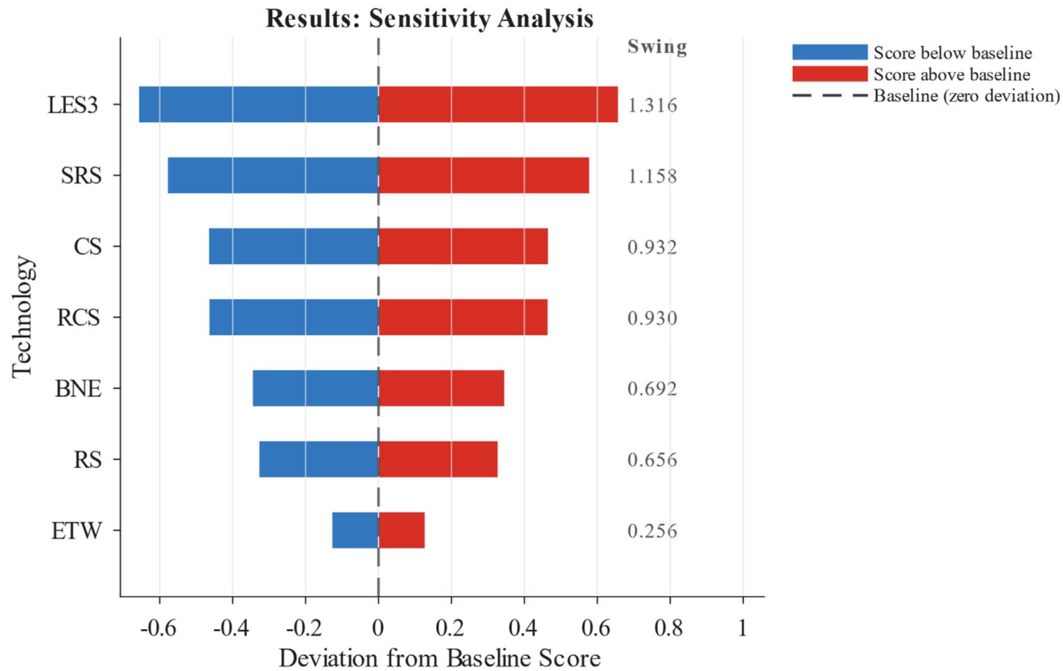

Fig. 12. Tornado diagram illustrating the results from sensitivity analysis.

across all scenarios despite SRS recording the second highest swing value, indicating stable relative performance under parameter perturbations.

RS retains the top rank in all the 27 scenarios, confirming the robustness of its leading position. Similarly, CS and SRS consistently occupy the second and third ranks, respectively, despite SRS exhibiting one of the highest swing values. The remaining technologies (BNE, ETW, RCS, and LES3) also maintain fixed rank positions throughout almost all scenarios, indicating complete ranking invariance across the full perturbation space. The only change in rank is observed for the ETW-RCS pair for the low-case of lunar applicability parameter (Scenario S20), where the ETW ranks behind RCS. However, given the small score margins of their ranking, the pair is considered as most sensitive to the change in weights which is demonstrated by this scenario.

Collectively, these results indicate that the overall ranking of RS and the stability of the top three technologies is preserved under the full set of perturbation scenarios, providing strong evidence for the robustness of the trade-off analysis.

5. Discussion

The results of the trade-off analysis are dependent on the quality and objectivity of the input data used to score each technology against the evaluation parameters. Several parameter scores in the present study are derived from qualitative assessments based on available literature and expert judgement, particularly for parameters where quantitative experimental data is either limited or unavailable. For example, in the case of BNE, there has been experimental work but not enough quantitative measurements for the separation performance and/or other operational outcomes which makes it rank lower. But with more experimental work, this can change in the future and the framework can be updated accordingly. While the structured scoring methodology and the sensitivity analysis mitigate the impact of individual scoring subjectivity, the substitution of qualitative assessments with quantitative experimental measurements would materially improve the accuracy and reproducibility of the framework.

A specific operational risk associated with RS that warrants discussion is the potential for sieve blinding, that is, the progressive occlusion of sieve apertures by fine or irregularly shaped particles that reduces classification efficiency over time. Lunar regolith is characterised by a wide particle size distribution, a high proportion of fine particles below 20 μm, and angular, abrasive particle morphologies that differ substantially from terrestrial soils, creating conditions broadly conducive to sieve blinding in conventional sieving systems (Cannon et al., 2022). However, as demonstrated in the literature (Zhao et al., 2025), sieve blinding in rotary sieve configurations can be mitigated through various mechanical agitation methods. Therefore, sieve blinding is considered to be a manageable engineering challenge rather than a fundamental barrier to the operational viability of RS. Nevertheless, the extent of this risk under prolonged operational conditions and the relative effectiveness of different mitigation strategies warrants further evaluation.

An important aspect that needs further clarification is that the technologies under consideration in this work span a range of different TRL. It can be seen as inequitable to compare them on a similar scale. However, the low relative weight assigned to TRL (w = 0.01), reflects the position, that the functional performance of the system under lunar operational conditions is of greater importance at this stage than its current TRL giving the opportunity for high performing innovative early-development stage technologies to be a potential candidate for future maturation activities. Moreover, the framework is designed as a living reference instrument that can be updated as TRL levels evolve, ensuring that the relative weighting can be revisited and increased as the field matures and operational deployment timelines are more defined.

It should also be acknowledged that no single classification technology can optimally serve all potential lunar ISRU applications, given the diverse particle size distribution requirements imposed by different downstream processes. The present framework evaluates the candidate technologies against a broad set of criteria calibrated to reflect the general operational priorities of early-stage lunar ISRU, where mission requirements and in-situ regolith characterisation data remain incomplete and where broad applicability across a range of particle size requirements is therefore a more relevant selection criterion than optimisation for a single application. It should nonetheless be noted that technologies ranked lower in the present analysis may be better suited to specific application contexts. For instance, LES3, while not identified as the most promising candidate for a full-scale regolith processing plant, may represent a more suitable option for early-stage technology demonstration and validation in the context of rover-based mobile excavation and processing systems, where compactness and operational simplicity may outweigh other performance parameters as the primary selection criteria. Furthermore, as lunar ISRU operations mature and in-situ regolith data becomes available, it is anticipated that multiple complementary classification technologies may be deployed in series or in parallel to address the full range of particle size and throughput requirements across different mission phases. The recommendation of RS therefore reflects its broad applicability and robust performance across the evaluation parameters rather than a claim of universally optimal solution for all particle size classification requirements.

Finally, it should be noted that the current evaluation is conducted at the technology selection level and represents a comparative assessment under a common set of evaluation criteria. The absolute performance of any individual technology under actual lunar surface conditions, including high vacuum, reduced gravity, extreme thermal cycling, and electrostatically charged regolith particles cannot be fully characterised from the available data. These environmental factors are partially captured through the lunar applicability parameter, which carries the second highest weight in the framework, but their combined effect on classification performance under operational conditions remains an important open question that the present study is not positioned to resolve.

6. Conclusions

The study conducted a systematic trade-off analysis of seven dry particle size classification technologies for lunar regolith processing, motivated by the need to identify the most suitable particle size classification method to support the future lunar in-situ resource utilisation (ISRU) infrastructure. A multi-criteria decision-making framework comprising 13 evaluation parameters, weighted to reflect the operational priorities of a lunar regolith processing system, was developed and applied to comparatively assess the seven technologies. The framework itself represents a standalone contribution of this work, providing a structured, transparent, and extensible basis for technology evaluation that can be refined and reapplied as new experimental data and operational insights become available. The trade-off analysis identifies Rotary Sieve (RS) as the most promising dry classification technology under the current state of technological development and available experimental evidence. The robustness of this outcome is confirmed by a one-at-a-time sensitivity analysis demonstrating that the ranking is robust against reasonable variations in the AHP-derived parameter weights.

Further research should prioritise the experimental validation of the RS system under relevant operational conditions, with emphasis on the quantitative characterisation of its key performance parameters, in particular separation efficiency, sieve blinding behaviour under prolonged operation, and performance under reduced gravity. Such experimental efforts will generate the empirical data necessary to replace the qualitatively derived parameter scores in the current framework with validated quantitative inputs, improving the accuracy and objectivity of future technology assessments.

Data availability

The datasets generated and analysed during the current study are available in the supplementary materials. Further data and/or related information can be made available from the corresponding author on request.

CRediT authorship contribution statement

Kulkarni Kunal: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Zabel Paul:** Writing – review & editing, Supervision, Funding acquisition. **Linke Stefan:** Writing – review & editing, Supervision. **Stoll Enrico:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asr.2026.07.115.

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