Original Research Article

Implications for Deep-Sea Mining Methods from Experimental Sediment Dispersion Modelling

Ari Kim[1], Diana Gao[1], Manuel Scharrer[2]

[1]*Farragut High School, 1237 Kingston Pike, Knoxville, TN 37934, United States;*
[2]*University of Tennessee, 527 Andy Holt Tower, Knoxville, TN 37996, United States*

ABSTRACT

This research aims to answer the question: to what degree do different deep-sea mining collection methods affect sediment plume dispersion? Critical minerals found in manganese nodules, which are extracted during deep-sea mining, are crucial for renewable technologies. However, the effects that collecting these nodules may have on the environment remain largely unknown. We hypothesized that the hydraulic suction model, a common collection method, would create less sediment dispersion in the water column. The goal of this research was ultimately to evaluate how the two major deep-sea mining collection methods' sediment disturbance compare. To achieve this goal, deep-sea collection processes were modelled while data was collected in disturbance levels, number of nodules collected, and visual sediment disturbance. Contrary to the primary hypothesis, no statistically significant differences were observed in maximum or final sediment disturbance between the static comb and hydraulic suction methods, suggesting that most disturbances were caused by the mining vehicle, not the collection methods. Ultimately, these small-scale findings demonstrate that to reduce harmful sediment plumes, future research should focus on engineering the mining vehicle itself to become more hydrodynamic rather than simply focusing on the collection tool.

Keywords: deep-sea mining; sediment; environmental effects; disturbance; sediment plume; sediment dispersion

INTRODUCTION

Alternative methods of element sourcing such as deep-sea mining have gained recent traction as more elements are being labeled as critical minerals due to increased demand and shortage in sufficient domestic supply, resulting in a high dependence on other countries (1). Although several deposit types exist on the ocean floor which could be extracted through deep-sea mining (2), one of the most sought after is the manganese nodule (1). These manganese (Mn) nodules contain a variety of elements–such as Mn, Co, Ni and Cu–that are crucial for the modern way of life and renewable energy technologies, including the improvement of lithium-ion battery performance and solar energy storage (3).

Even so, deep-sea mining for manganese nodules results in many negative implications for the ocean region. The process of driving manganese nodules out of the sediment often leaves tracks of compacted debris, disturbing microbiomes and smothering filter-feeding organisms (4). Behind the collection vehicle, suspended particles rise the water column, resulting in sediment plume.

Corresponding author: Ari Kim, E-mail: kima92193@gmail.com.

Accepted July 28, 2026
https://doi.org/10.70251/HYJR2348.44533543

In typical deep-sea conditions, the possibility of sediment suspension is minimal with low concentrations of particles being uprooted when natural sediment disruption does occur (5). However, with deep-sea mining, sediment is constantly displaced into the water (5). The sediment plume generated by deep-sea mining results in large concentrations of suspended particles and irregular turbidity, influencing currents that reach the upper portions of the ocean (5). It is said to take years for this sediment to settle during which sediment can be pushed upwards to 1000 km, reaching the mesopelagic zone and even parts of the upper bathypelagic zone (6, 7). Sediment is thus displaced across a wide expanse of land, often causing suffocation and burial of benthic fauna outside of mining areas (8).

Though the long-term detriment of deep-sea mining is clear, the type and magnitude of its effects on ocean conditions remain largely a mystery. Most studies that consider its environmental impacts use vague words such as "possibly" and "potential" due to the number of unknowns and difficulties experimenting in deep-sea mining sites (9). In particular, respective advantages and disadvantages of various collection methods on sediment and efficiency have not yet been discussed in detail. Thus, with the demand for deep-sea mining's critical minerals set to increase 10-fold by 2040 and the number of mining sites set to quadruple by 2035 (10), the catastrophic effects of collection methods in deep-sea mining must be evaluated to prevent further damage to the oceans. This research aims to inform the community by detailing various impacts of deep-sea mining on sediment dispersion and disturbance.

Of the vehicles that move the collection systems, the most common walking type is the self-propelled crawler. The model promotes the least disturbance of the seabed while avoiding obstacles with strong operability due to the motion of the wheels (11). Though the model requires high energy consumption and remains susceptible to sliding, many countries–including China, Germany, and Korea–have accepted the self-propelled crawler as the primary vehicle for collection. Thus, the self-propelled crawler was modelled as the vehicle/cart in the following experiment, serving the main purpose of the vehicle: holding and transporting collection systems (12).

Regarding extraction models, the two most explored methods are the teeth-comb system and hydraulic suction system. Therefore, these two collection methods were selected to be modelled in this publication.

Proposed by Ocean Minerals Company, the comb collection system uses comb shaped teeth to extract manganese nodular particles from the sediment (13). Such a method reduces energy consumption as the comb dislodges nodules without fluid pressure (11). In this publication, to reduce complexity, a static comb setup, rather than the more complex rotating collector, was selected and built into the model system.

In the suction collection method, the suction acts as a vacuum to draw nodules through a pipe and into the elevation system. The method remains reliable in operation; however, the vacuum requires a significant amount of hydraulic pressure to extract the nodules and is known for causing significant sediment plume (14, 15). For mining purposes, either a large seafloor surface is mined, or a highly automated mechanism is used to extract only the manganese nodules.

Due to the insufficient research on the environmental effects of deep-sea mining, especially with respect to sediment dispersion, the topic was chosen. The evaluation of the collection methods' sediment disruption was achieved through a laboratory size experimental replication of deep-sea mining techniques and the quantification of differences in sediment dispersion. These methods hoped to answer the question: how do the different deep-sea mining collection methods affect sediment plume dispersion?

The objectives of this study were to recreate deep-sea mining conditions in a laboratory setting, compare the relative collection efficiency of the static comb and hydraulic suction systems, and evaluate the sediment disturbance and plume dispersion produced by each method. It was hypothesized that the hydraulic suction collection model–which creates a centripetal, suction force–would create less sediment dispersion in the water column while also being more effective in collecting manganese nodules.

METHODS AND MATERIALS

Experimental Design

An aquarium tank of 60 gallons was obtained and used for lab experiments. Plexiglass was used to create two walls with a vertical 5.0 cm gap at the height of the seafloor. In addition, to enable the replication of the deep-sea ocean current during selected experiments, an aquarium tank pump was used. The suction half was placed on one side of the aquarium behind the plexiglass barrier close to the surface, and the discharge half of the pump was placed behind the plexiglass on the other side of the experiment.

Two pulley bars (each made with a 5.0 mm diameter rod, two axles, and two binder clips) were glued onto one of the Plexi walls such that one bar was near the bottom of the tank while the other was right below the top rim of the tank. This allowed the use of strings to pull the mining cart along the replicated seafloor while minimizing friction and simplifying the experiment as the cart itself would not require a motorized setup.

To stabilize the lower portion of the replicated seafloor, sand was poured into the main portion of the tank until a height of 3.0 cm. Due to sand's granular texture (16), it served as a solid foundation which prevented the upper layer from sliding against the tank walls (17). Then, a 1.0 cm layer of bentonite clay granulate was added and slowly hydrated. Due to bentonite's soft compressibility and smaller particle size (18), bentonite gave a more accurate representation of deep-sea sediment due to its ability to mimic vehicle sinkage and sediment disturbance. With the expansion of the clay on hydration, the bentonite increased to 2 cm. Such a layered setup allowed for the qualitative estimation of depth in sampling during mining using the relative amount of sediment and clay mineral portion extracted.

Water was gradually mixed with 4.0 kg of salt and added to the tank until the tank's water level reached a height of 33.0 cm, replicating sea water salinity. The target salt mass was estimated using the approximate equivalence of 1 L seawater ≈ 1 kg for bench-scale preparation. While PSU is formally defined as grams of salt per kilogram of seawater rather than per liter, the resulting difference at this scale was considered negligible for the purposes of experimental modelling.

To finish modelling deep-sea conditions, pebbles (used to simulate Mn nodules) were added randomly to simulate the disorganized manner in which manganese nodules are found.

A total of three independent experiment replicate trials were conducted for the static comb method and two independent experiment replicate trials for the hydraulic suction method. Additionally, a current was simulated with the static comb system for two trials. Due to time constraints, unequal numbers of trials were performed per method. For the same reason, the suction method was unable to be tested with a current.

The static comb trials were first completed, along with the static comb and current trials. Then, the trials for the hydraulic suction were completed. A limitation arose from this fixed order of trials due to the possibility of change in experimental settings over time. However, this limitation was not cause for major concern as data was analyzed based upon the beginning illumination levels and when the water was recorded to be fully disturbed, minimizing any systematic error that could have resulted from sensor calibration differences.

After each trial, the simulated ocean floor was manually smoothed out. Additionally, the extracted clay particles and pebbles were recorded and redistributed into the path which the pebbles were extracted from. The process assisted in resetting experimental conditions and randomized the placement of the nodules across the trials.

Modelling of the Comb System

A vehicle consisting of two connected sets of wheels was assembled. To minimize sliding along the slippery clay sediment, spikes were added to the wheels.

For this method, a plastic comb was added to the second set of wheels, the design based on a previously designed rotating comb collection system (19). The height of the comb was chosen so that the lower end was in line with the bottom of the mining cart's wheels, allowing for Mn nodule mining without the comb becoming lodged into the lower levels of sediment. Overall, much of the collection systems modelling was not based upon previous research but rather based upon logic and known resources. Thus, not much research is able to support the choices made regarding collection simulations. Two strings were attached to the front half of the cart and looped around both sets of axles. These strings were pulled down at a steady rate of approximately 3.81 cm per second. The speed was calculated based on 5 repeated speed tests and kept approximately the same for all experiments in order to minimize variable parameters.

Data was collected with a light sensor positioned such that light intensity 2-3 cm above and parallel to the movement of the mining cart was recorded. In addition, a light source was placed on the opposite side of the sensor. Rather than calibrating the sensor, the data obtained during each trial in terms of illumination (lux) was compared to the beginning illumination value to determine the disturbance percentage during analysis. The number of nodules collected after each experiment were manually counted. In addition, qualitative observations of camera-recorded trials were viewed perpendicular to the cart's movement from the side and top view.

Modelling the Comb System with Current

To determine the difference of modelling deep-sea mining with or without a current, the water pump was activated during the modelling of the comb system.

Modeling of the Suction Collection

To minimize variable parameters between the different experiments, all variables were kept constant for the experiments. Thus, the same cart design of the comb trials was used with only the comb setup exchanged for a suction mining setup.

A suction pump was installed based on previous research that had aimed to mimic the suction collection system in a small scale (20). The suction setup was designed such that a suction pipe was positioned with the open end at the same depth as the bottom of the wheels of the mining cart. The other end of the suction pipe led to a water pump. Vehicle speed and data collection were kept the same as the comb trial.

Similarly to the static comb system, due to lack of resources and complexity, there was minimal research available that was able to guide our decisions regarding the modelling of the suction system.

Collection Area Determination

The mined area for each trial was calculated from the collection head width and the travel distance of the cart. Travel distance was measured using the calibrated grid on the front glass wall of the experimental tank. Both collection methods were mounted on the same cart, resulting in a consistent swept path and penetration depth (2 cm) across trials.

Controlled Conditions

The temperature was kept at room temperature. The pressure was kept at 1 atm. The same vehicle that carried the nodule collecting systems was used for each trial. There was no change in the salinity of the water.

Converting Raw Light Sensor Data for Analysis

The light sensor detected illumination; thus, in order to obtain comparable levels of disturbance between experiments, a scale to quantify the percent disturbance was necessary. Under fully disturbed conditions, illumination was, within signal noise, approximately 0 lux, defining the upper bound of the disturbance metric. This was confirmed through a manual energetic disturbance of the sediment in the experiment while the light sensor was recording. Initial undisturbed illumination ranged from 400 to 700 lux (0% disturbance). Differences arose from slight variation of exact lighting conditions during experiments and alignments of the illumination sensor. To compare trials, illumination measured approximately 3–5 cm above the cart was normalized to the initial value and expressed as disturbance percentage:

$$\textit{Disturbance percentage} \sim 3\text{–}5\textit{cm above cart} = 100 - \frac{lux}{lux_{initial}} \times 100$$

Statistical Approach

Disturbance and pebble collection measurements were recorded simultaneously for each experimental trial. Sensor anomalies affected disturbance measurements but did not affect pebble counts as the pebbles were counted manually. Consequently, trials excluded from disturbance analyses retained valid collection data. For such trials, collected disturbance measurements were not analyzed to determine the average sediment plume and disturbance levels of each method. The disturbance-per-pebble ratio was calculated only from matched trials for which both valid disturbance measurements and corresponding pebble collection measurements were available. Trials excluded from the disturbance analysis because of sensor anomalies were also excluded from the disturbance-per-pebble calculation.

Due to limited sample sizes, statistical comparisons should be interpreted as exploratory rather than confirmatory. Welch's t-test was selected as it does not assume equal variances between groups. However, assumptions of normality could not be reliably assessed given the small sample sizes. Results are reported as mean ± SD, with two-sided p-values. Because only one corrected current trial was available, the static-comb-with-current condition was not included in inferential comparisons and is described only qualitatively and descriptively.

In addition to p-values, Hedge's g effect sizes were calculated to quantify the magnitude of differences between groups and to account for small sample sizes. Effect sizes were interpreted using conventional thresholds of approximately 0.2 (small) 0.5 (medium), and 0.8 (large).

RESULTS

Static Comb Method

As seen in Figure 1, the disturbance-time curve exhibited four general phases: an initial ~10 s baseline, a rapid increase after cart motion began, a peak when the sediment wave reached the tank wall, and a gradual decline as suspended particles dispersed and settled. Similar curve shapes were observed for the suction method and the static comb method with current. For the static comb trials, maximum disturbance values were 31.8%, 18.4%, and 16.8% (mean 22.4%), while final disturbance values were 8.6%, 2.4%, and −0.3% (mean 3.6%).

As the vehicle moved across the sediment bed, it generated a suspended-sediment plume that propagated outward from the front and sides of the vehicle, reducing water clarity along the direction of motion (Figure 2A). The vehicle also left a distinct trail of displaced surface sediment (Figure 2B), producing a visually rugged and uneven track than the surrounding undisturbed bed (Figure 2C).

Suction Method

The measured maximum disturbance values for the two suction trials were 22.7% and 18.8%, with a mean of 20.8%. Final disturbance values were 9.0% and 1.7%, with a mean of 5.3% (Figure 3).

The suction cart collected an average of 300 mL of

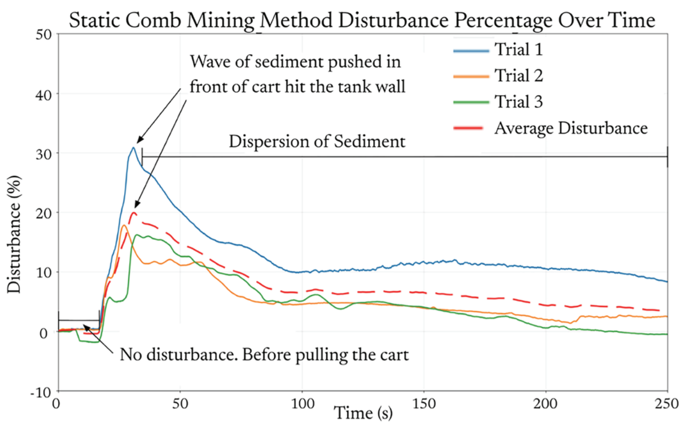

Figure 1. *Comparison of sediment disturbance calculated from the data obtained through the light sensor over time of the 3 trials that utilized the static comb collection method. Disturbance, in relation to the initial disturbance of the water (0%), peaked early as sediment built up in front of the cart and was pushed upwards and outwards, then gradually decreased as particles dispersed and settled.*

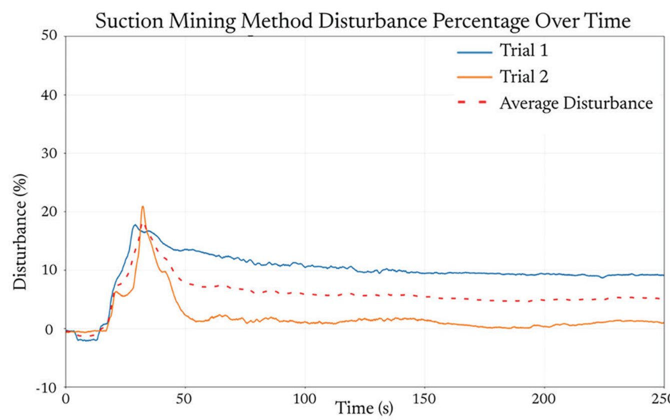

Figure 3. *Graphical comparison of sediment disturbance over time from the simulated trials with the hydraulic suction collection method. Similarly to Figure 1, disturbance rose quickly during the first 50 seconds and then declined more gradually over the rest of the experiment.*

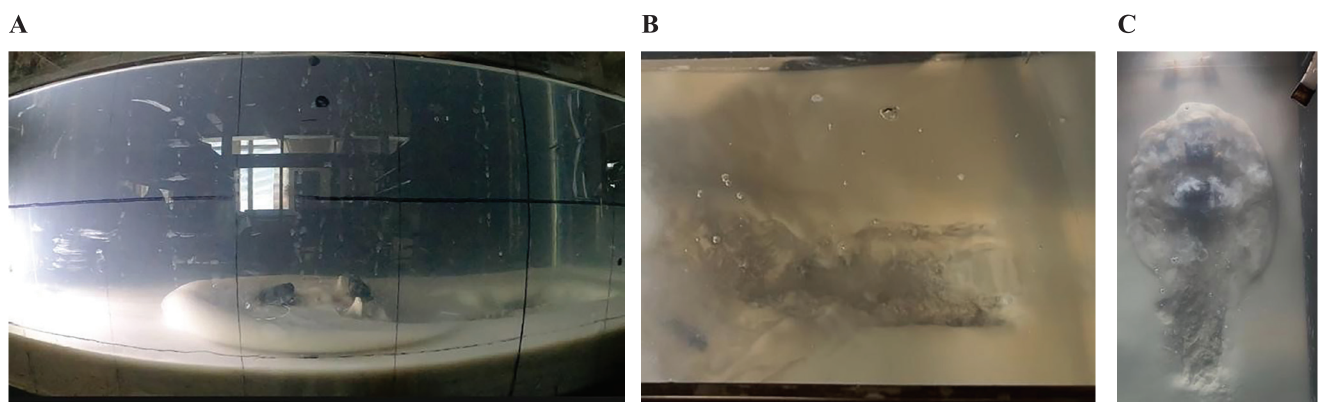

Figure 2. *Visual documentation during the trials using the static comb collection system. (A) Side view of the experimental tank during the trial. (B) Overhead view detailing the resulting sediment trail after the vehicle had just gone through. (C) Full top view capturing the broader plume distribution. The scale was standardized across all views, trials, and mining methods by using a grid and fixed camera positions through the study.*

sediment-laden water containing both bentonite clay and visible sand. Because sand was present only in the lower sediment layers of the experimental design, its recovery by the suction method indicates that suction entrained sediment from below the 2 cm operating depth more effectively than the static comb.

As the suction vehicle moved across the sediment bed, it generated a concentrated sediment plume around the inlet that reduced water clarity near the vehicle (Figure 4A). Sediment directly beneath the inlet was disturbed and partially removed, producing a localized depression in the bed (Figure 4B). The trail left behind was relatively smooth and shallow compared with the surrounding sediment (Figure 4C).

Exploratory Current-Condition Analysis

As an exploratory analysis, the current-only control was subtracted from the single static-comb-with-current trial to estimate disturbance attributable to the comb under active flow. The corrected disturbance reached a maximum of 12.5% and a final value of 24.6% (Figure 5). Because these values were derived from single observations without replication, they are presented descriptively and were not included in statistical comparisons.

Under current conditions, the static comb produced a broad suspended-sediment plume as surface sediment was scraped and displaced forward by the comb (Figure 6A). Ambient flow transported fine particles downstream, creating a wider and more dispersed sediment plume than in no-current trials (Figure 6A). The resulting seafloor track appeared somewhat smoother than that of the static comb without current, likely due to flow-driven redistribution of disturbed sediment, but it remained rougher and more disrupted than the trail produced by the suction method (Figure 6D).

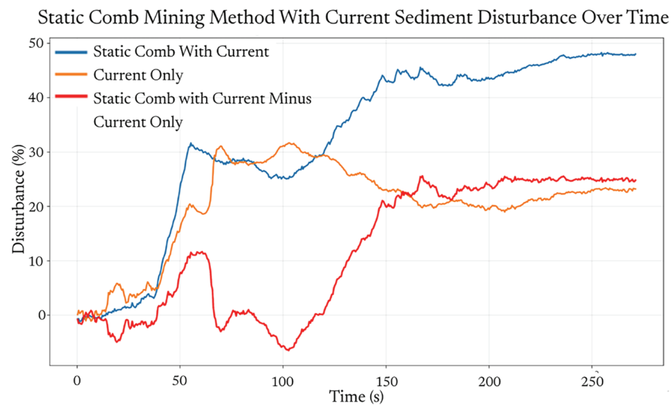

Figure 5. Exploratory analysis of sediment disturbance under simulated current conditions. Disturbance is shown for one static-comb-with-current trial, one current-only trial, and the corrected disturbance obtained by subtracting the current-only measurement from the static-comb-with-current measurement. Because these data are based on single observations without replication, they are presented for exploratory purposes only and are not directly comparable to the replicated static-comb and suction conditions.

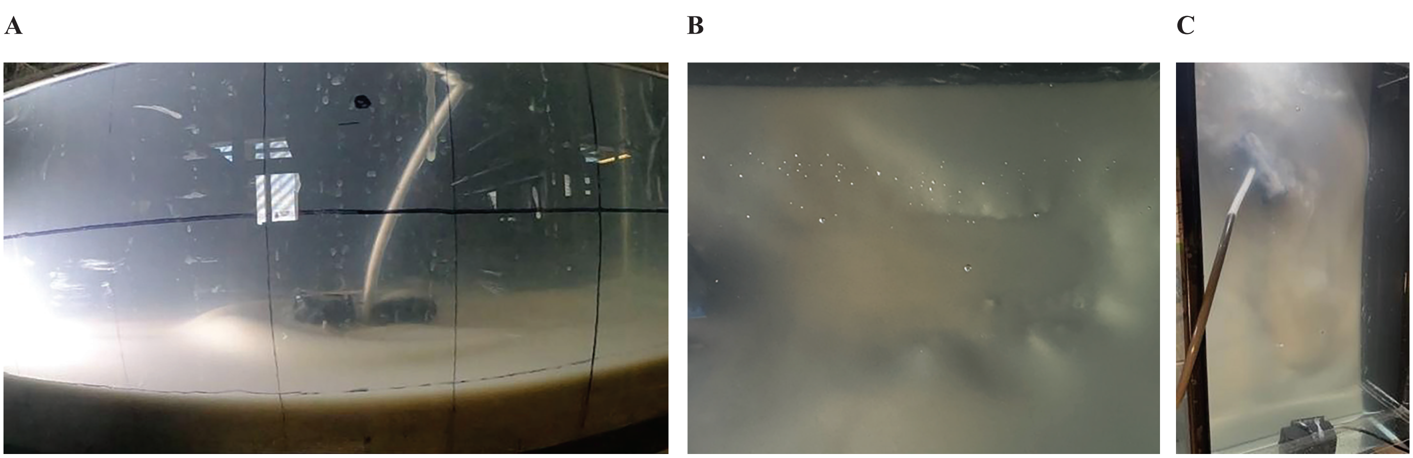

Figure 4. Visual documentation of during and after the testing of the suction mining collection method. (A) Side view of the experimental tank during the suction trial, displaying the mechanism and initial sediment intake. (B) Overhead view detailing the resulting sediment trail and floor disturbance. (C) Full top view capturing the broader plume distribution and water turbidity.

A

B

C

D

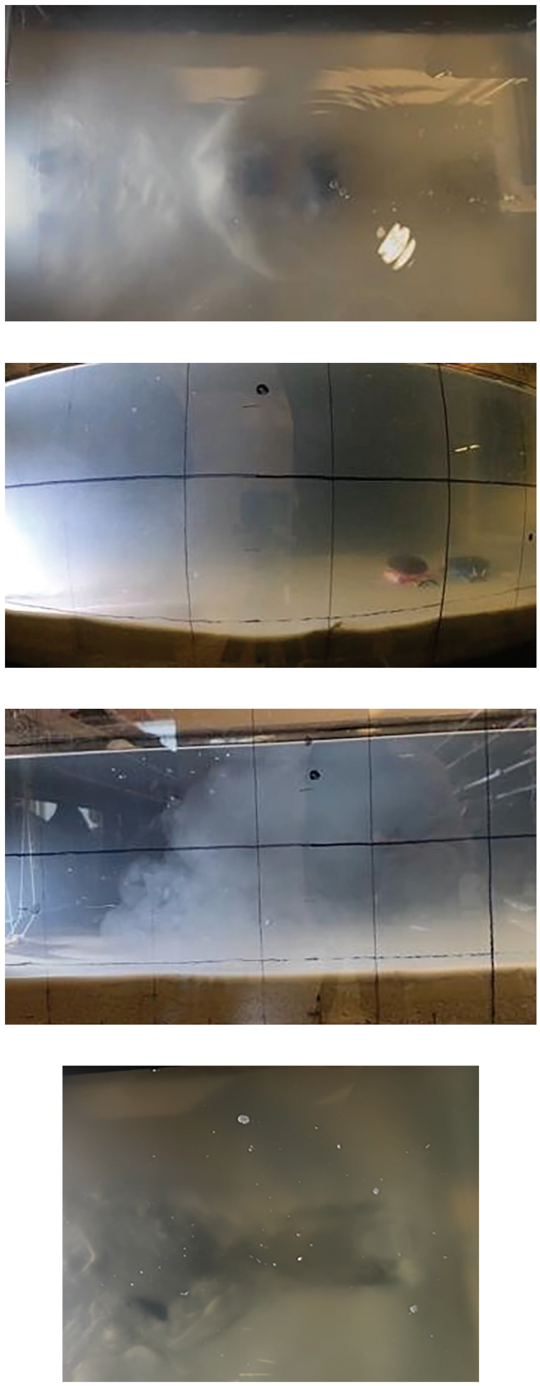

Figure 6. *Visual documentation of the experimental trials and sediment plumes of static comb with current and only current trials. (A) Top view captured during the active experiment, detailing the outward sediment plume of the static comb with current trial. (B) Side view of the experimental setup for the static comb with a simulated current trial. (C) Side view documenting the sediment behavior during the current-only trial. (D) Top view showing the remaining trail following the experiment of the static comb with the current trial.*

Statistics

The static comb collected 10, 13, 16, and 14 pebbles across four trials (mean 13.3 ± 2.5; 95% CI: 10.85 to 15.75) (Figure 7). The suction method collected 26, 37, and 34 pebbles across three trials (mean 32.3 ± 5.7; 95% CI: 25.850 to 38.750).

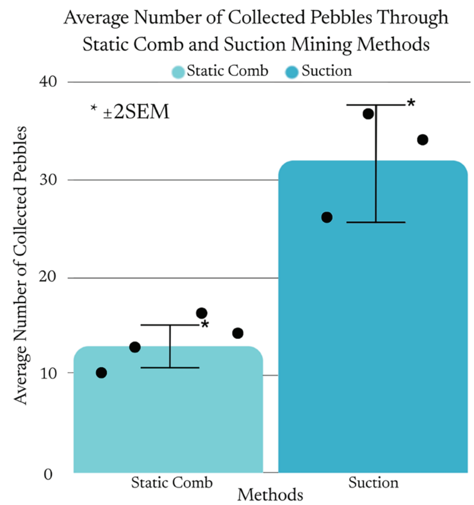

Figure 7. *Bar charts comparing average number of collected pebbles in the static comb versus suction method. Data for the static comb trials are presented as 13.3 ±2.5 (n = 4 trials). The static comb and current trial were not included. Data for the suction trials are presented as 32.3 ±5.7 (n = 3 trials). Individual trial values are shown as overlaid scatter points. Static comb scatter values include 10, 13, 16, and 14. Suction scatter values include 26, 37, and 34.*

Pebble collection differed substantially between methods (Welch's $t = -5.43$, $p = 0.018$; Hedge's $g = 3.92$), indicating that the suction method collected more simulated nodules than the static comb under the tested conditions.

When normalized by mined area, the static comb collected 0.8 pebbles/cm^2, whereas suction collected 12.7 pebbles/cm^2. Using reported means, disturbance per collected pebble was approximately 0.30% for the static comb and 0.16% for suction. Because this exploratory metric was calculated from the limited subset of matched trials with both valid disturbance and collection measurements, no formal statistical comparison was performed, and the values are presented descriptively only.

As shown in Figure 8A, the average maximum disturbance for the static comb method was 22.4 ± 8.2% (95% CI: 13.121 to 31.679), while the suction method reached an average maximum disturbance of 20.8 ± 2.8% (95% CI: 16.919 to 24.681). Exploratory observations under simulated current conditions are presented separately (Figure 5) because only a single corrected current trial was available.

The average final disturbance for the static comb method was 3.6 ± 4.6% (95% CI: -1.605 to 8.805), while the suction method reached an average disturbance of approximately 5.3 ± 5.2% (95% CI: -1.907 to 12.507) (Figure 8B). Exploratory observations under simulated current conditions are presented separately (Figure

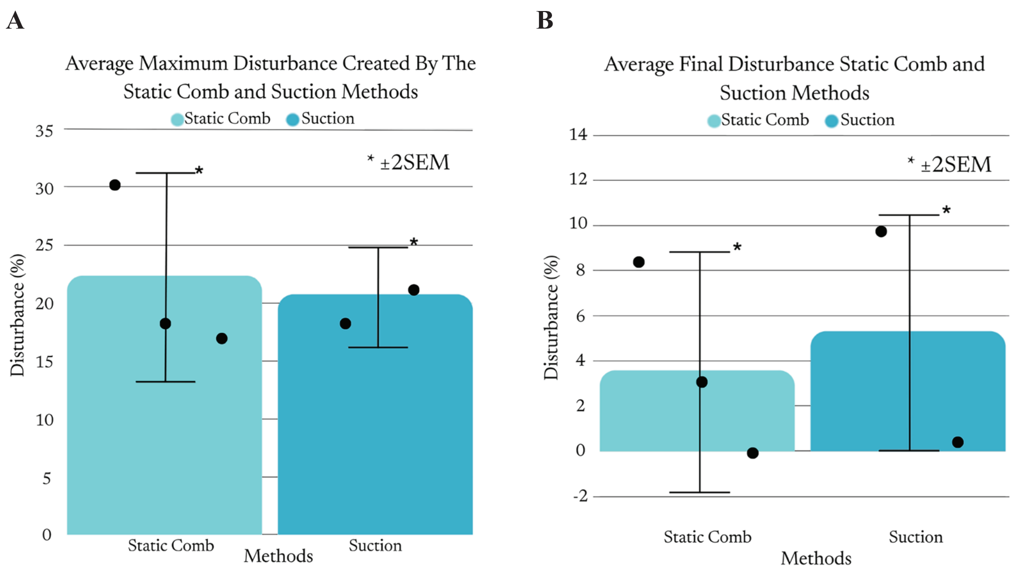

Figure 8. *Bar charts comparing mining methods' (suction vs static comb) efficiencies and final average disturbance. (A) Average maximum disturbance created by the static comb and suction methods. Data for the static comb trials are presented as 22.4 ±8.2% (n = 3 trials). The static comb and current trial were not included. Data for the suction trials are presented as 20.8 ±2.8% (n = 2 trials). (B) Average final disturbance created by the static comb and suction methods. Data for the static comb trials are presented as 3.6 ±4.6% (n = 3 trials). The static comb and current trial were not included. Data for the suction trials are presented as 5.3 ±5.2% (n = 2 trials). Individual trial values are shown as overlaid scatter points.*

Table 1. *Summary of key quantitative outcomes for the static comb and hydraulic suction collection methods. Values are reported as mean ± standard deviation (SD), sample size (n), and 95% confidence interval (CI). Maximum disturbance represents the peak normalized disturbance observed during a trial, while final disturbance represents disturbance at the end of the recording period. Pebbles collected represent the total number of simulated nodules recovered per trial. Statistical comparisons between methods were conducted using Welch's two-sample t-tests, and Hedges' g was calculated to estimate effect size. Effect sizes of approximately 0.2, 0.5, and 0.8 correspond to small, medium, and large effects, respectively. Due to limited sample sizes (comb: n = 3 disturbance trials and n = 4 collection trials; suction: n = 2 disturbance trials and n = 3 collection trials), results should be interpreted cautiously. Statistical significance was evaluated at α = 0.05.*

Outcome	Static Comb	Suction	Comparison	Interpretation
Maximum Disturbance	22.4 ± 8.2% (n = 3; 95% CI [13.1, 31.7])	20.8 ± 2.8% (n = 2; 95% CI [16.9, 24.7])	Welch's t = 0.31, p = 0.778; Hedge's g = 0.23	No statistically significant difference; small effect size
Final Disturbance	3.6 ± 4.6% (n = 3; 95% CI [16.9, 24.7])	5.3 ±5.2% (n = 3; 95% CI [-1.907, 12.507])	Welch's t = -0.38, p = 0.737; Hedge's g = 0.30	No statistically significant difference; small effect size
Pebbles Collected	13.3 ±2.5 (n = 4; 95% CI [10.9, 15.8])	32.3 ± 5.7 (n = 3; 95% CI [25.9, 38.8])	Welch's t = -5.43, p = 0.018; Hedge's g = 3.92	Statistically significant difference; large effect favoring suction

5). Comparison between the static comb and suction methods did not show evidence of a statistically significant difference in maximum disturbance (Welch's $t = 0.31$, $p = 0.778$; Hedge's $g = 0.23$) or final disturbance (Welch's $t = -0.38$, $p = 0.737$; Hedge's $g = 0.30$). These results should be interpreted cautiously because of the small sample sizes.

DISCUSSION

The main quantitative result of this study is that the suction method improved collection efficiency without producing a measurable reduction in optical disturbance under the present bench-scale conditions. Maximum and final disturbance values did not differ clearly between the static comb and suction methods, whereas pebble collection was substantially higher for suction. Although the suction method exhibited a lower disturbance-per-pebble ratio, this derived metric was not formally tested and should therefore be interpreted cautiously. Additional studies using matched disturbance and collection datasets are needed to determine whether the observed difference reflects a true efficiency advantage. The similarity in disturbance measurements between methods suggests that factors common to both systems, including vehicle translation, may contribute substantially to sediment resuspension. Because both methods used the same cart platform and both generated a sediment wave at the front of the vehicle, this shared mechanical disturbance may have obscured smaller differences attributable specifically to collector design. In that sense, the results suggest that collector choice influences recovery efficiency more strongly than it influences bulk sediment plume generation in this experimental configuration.

The qualitative observations nevertheless indicate meaningful mechanical differences between the methods. The static comb produced a rougher and more visibly redistributed trail, consistent with scraping and forward displacement of surface sediment. In contrast, the suction system generated a more localized disturbance near the inlet, leaving a smoother path, although it also entrained deeper material in this configuration. These differences may still be environmentally relevant even when the optical disturbance metrics are similar.

The current-condition experiment further suggests that ambient flow may reduce local sediment buildup while increasing sediment plume persistence and transport distance. However, the present dataset is insufficient for formal comparison because only one corrected current trial was available, so additional replicated trials under controlled flow conditions are needed before stronger conclusions can be drawn.

A primary limitation of this work is the modest replication, especially for the suction and current-condition experiments. As a result, these findings should be interpreted as preliminary trends from a controlled pilot study rather than as definitive estimates of method performance under operational conditions. The limited sample size reduces statistical power and makes small between-method differences difficult to resolve with confidence. In addition, the benchtop system does not fully capture deep-sea conditions, since sediment transport was constrained by tank geometry, the vehicle was manually pulled rather than autonomously driven, and environmental variables such as pressure, temperature, and realistic background flow were not reproduced. Nevertheless, the controlled side-by-side design remains informative: both collection methods were evaluated using the same vehicle platform and sediment test environment, allowing an internally consistent comparison of disturbance patterns and collection efficiency. These results are therefore best viewed as hypothesis-generating and design-informing for future larger-scale studies.

A practical implication of this study is that environmental mitigation should not focus only on the collector head. Although collector efficiency remains important, especially because a more efficient system may generate less disturbance per nodule recovered, the present results suggest that the vehicle platform itself may be a major driver of sediment resuspension. This means that reducing mining impacts will likely require system-level optimization, including collector design, vehicle speed, weight distribution, seafloor contact geometry, and interaction with ambient currents. In other words, improving recovery efficiency alone may not substantially reduce sediment plume formation if cart-induced disturbance remains the dominant source of sediment mobilization. At the same time, disturbance relative to resource recovery remains an important performance metric, since a method that achieves greater recovery at comparable disturbance may still reduce impact per unit resource extracted.

CONCLUSION

Overall, this pilot study suggests that hydraulic suction may provide greater collection efficiency than a static comb design in this bench-scale system, though sediment disturbance appears to be strongly influenced by vehicle motion itself. It is most conclusive that suction improved recovery efficiency under the tested conditions, but the present dataset does not show a clear decline in overall optical disturbance between methods per mining vehicle movement. Rather, the results suggest that bulk sediment plume formation in this setup may have been influenced more strongly by translation of the vehicle across the sediment bed than by the collector mechanism alone. Because replication was limited due to long breaks required for equilibration of the experiment between runs, particularly the suction and current-condition experiments, these findings should be interpreted as preliminary and require confirmation under more realistic and automated conditions. Nevertheless, the study provides a useful pilot-scale comparison that can guide future collector design, vehicle optimization, and environmental assessment.

ACKNOWLEDGEMENTS

Research was conducted under the supervision of Manuel Scharrer, University of Tennessee Knoxville professor of critical minerals. Dr. Scharrer has a special interest in understanding ore forming processes and the behavior of critical minerals.

FUNDING SOURCES

Funding from the University of Tennessee, Knoxville was received to obtain materials such as the tank, bentonite, salt, sand, water pump, and gravel.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this work.

REFERENCES

1. U.S. Government Accountability Office. Deep-sea mining could help meet demand for critical minerals, but also comes with serious obstacles [Internet]. Washington (DC): U.S. Government Accountability Office; 2021 Dec 16 [cited 2026 Feb 16]. Available from: https://www.gao.gov/blog/deep-sea-mining-could-help-meet-demand-critical-minerals%2C-also-comes-serious-obstacles
2. Fu Y, Li Z, Chew D, Hollings P, Peng J, Chen J, *et al*. Deep-sea rare earth element-rich sediments: a review of distribution, carriers and petrogenesis. *Glob Planet Change*. 2025; 252: 104870. doi:10.1016/j.gloplacha.2025.104870.
3. Committee on Natural Resources. Committee explores the potential of deep-sea mining to expand American mineral production [Internet]. Washington (DC): U.S. House of Representatives; 2025 Apr 29 [cited 2026 Feb 16]. Available from: https://naturalresources.house.gov/news/documentsingle.aspx?DocumentID=417070
4. Glover AG, Arias MB, Bribiesca-Contreras G, Copley JT, Dahlgren TG, Drazen JC, *et al*. The environmental impacts of deep-sea mining. *Curr Biol*. 2026; 36 (9): R400-R419. doi:10.1016/j.cub.2026.03.014.
5. Sha F, Xi M, Wen Z, Chen X, Zuo Y, Xu J, *et al*. A review on plumes generation and evolution mechanism during deep-sea polymetallic nodules mining. *Ocean Eng*. 2024; 298: 117188. doi:10.1016/j.oceaneng.2024.117188.
6. Muñoz-Royo C, Peacock T, Alford MH, Smith JA, Le Boyer A, Kulkarni CS, *et al*. Extent of impact of deep-sea nodule mining midwater plumes is influenced by sediment loading, turbulence and thresholds. *Commun Earth Environ*. 2021; 2 (1): 148. doi:10.1038/s43247-021-00213-8.
7. Wu Z, Zhang X, Jin S, Liu J, Liu X, Li L, *et al*. Analysis of sediment disturbance and plume dispersion characteristics induced by deep-sea polymetallic nodule hydraulic collectors. *Appl Ocean Res*. 2025; 156: 104462. doi:10.1016/j.apor.2025.104462.
8. Yao W, Tian C, Teng Y, Diao F, Du X, Gu P, *et al*. Development of deep-sea mining and its environmental impacts: a review. *Front Mar Sci*. 2025; 12: 1598584. doi:10.3389/fmars.2025.1598584.
9. Koschinsky A, Heinrich L, Boehnke K, Cohrs JC, Markus T, Shani M, *et al*. Deep-sea mining: interdisciplinary research on potential environmental, legal, economic, and societal implications. *Integr Environ Assess Manag*. 2018; 14 (6): 672-91. doi:10.1002/ieam.4071.
10. International Energy Agency. Growth in demand for selected minerals from clean energy technologies by scenario, 2040 relative to 2020 [Internet]. Paris: International Energy Agency; 2023 May 11 [cited 2026 Feb 16]. Available from: https://www.iea.org/data-and-statistics/charts/growth-in-demand-for-selected-minerals-from-clean-energy-technologies-by-scenario-2040-relative-to-2020
11. Zhang Q, Chen X, Luan L, Sha F, Liu X. Technology and equipment of deep-sea mining: state of the art and perspectives. *Earth Energy Sci*. 2025; 1 (1): 65-84. doi:10.1016/j.ees.2024.08.002.
12. Wang H. Underwater driving subsystem. In: Wang H, editor. Encyclopedia of Ocean Engineering. Singapore:

Springer. 2022; p. 2057-63. doi:10.1007/978-981-16-2015-5_299-1.
13. Wang Z, Fang Z, Zang Z, Zhang J. Experimental study on the hydrodynamic characteristics of a fixed comb-type floating breakwater. *Water (Basel)*. 2023; 15 (15): 2689. doi:10.3390/w15152689.
14. Amudha K, Kumar D, Gopkumar K, Balaji R, Sharma R. Numerical and experimental investigation of a Coandă-effect-based hydraulic collector for deep-sea polymetallic nodules. *Ocean Eng*. 2026; 363: 126448. doi:10.1016/j.oceaneng.2026.126448.
15. Jiang M, Wu H, Yang Y, Chen B. Research on the suction hydraulic collection characteristics of deep-sea cobalt-rich crusts based on waterjet-assisted methods. *Ocean Eng*. 2026; 343 (Pt 3): 123354. doi:10.1016/j.oceaneng.2025.123354.
16. Shackelford CD. Laboratory diffusion testing for waste disposal—a review. *J Contam Hydrol*. 1991; 7 (3): 177-217. doi:10.1016/0169-7722(91)90028-Y.
17. Nguyen DT, Khoo BC, Le-Cao K, Bertevas E, Phan-Thien N. Force measurements on an inclined plate moving a sediment/sand bed. *Ocean Eng*. 2021; 219: 108365. doi:10.1016/j.oceaneng.2020.108365.
18. Brandes HG. Geotechnical characteristics of deep-sea sediments from the North Atlantic and North Pacific oceans. *Ocean Eng*. 2011; 38 (7): 835-48. doi:10.1016/j.oceaneng.2010.09.001.
19. Xu L, Li X, Liu Y, Hong Z. Deep-sea polymetallic nodule mining: a review of cost reduction and efficiency technologies. *Int J Min Sci Technol*. 2026; 36 (6): 1121-47. doi:10.1016/j.ijmst.2026.04.007.
20. Deng L, Lu H, Liu S, Hu Q, Yang J, Kang Y, *et al*. Particle anti-accumulation design at impeller suction of deep-sea mining pump and evaluation by CFD-DEM simulation. *Ocean Eng*. 2023; 279: 114598. doi:10.1016/j.oceaneng.2023.114598.