

Investigating the Impact of Soil Properties and Gravel Cover on Wind Erosion Intensity in Eastern Isfahan

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Received: 06 August 2026, Accepted: 20 August 2026, Online First: 04 September 2026

ABSTRACT

This study aimed to analyze the impact of the physicochemical properties of soil and surface gravel cover on wind erosion intensity across different geomorphological units in eastern Isfahan. A total of 27 soil samples were collected from nine different geomorphological units. The physical properties (soil texture, gravel percentage, bulk density, saturation moisture) and chemical characteristics (EC, pH, calcium, magnesium, potassium, calcium carbonate) of the samples were determined. Wind erosion simulation experiments were conducted using a wind tunnel device at three levels of gravel cover (control, 15%, and 30%) and at three wind speed levels (threshold, twice the threshold, and four times the threshold). Data were analyzed using three-way ANOVA and multivariate regression. The results showed that increasing gravel cover percentage significantly reduced wind erosion intensity across all geomorphological units. Higher wind erosion was observed in soils with high clay content and salinity. Multivariate regression analysis indicated that calcium, magnesium, and calcium carbonate had the most significant positive impact on increasing soil resistance to erosion. Additionally, increasing wind speed exponentially raised soil loss, especially in sensitive landforms such as playas and mining areas. The combination of favorable physicochemical properties and surface gravel cover can significantly reduce wind erosion intensity. The findings highlight the necessity of conservation planning based on regional soil characteristics and wind speed for effective desert land management.

Keywords: Wind erosion, gravel cover, soil properties, wind tunnel, geomorphology of eastern Isfahan

INTRODUCTION

Wind erosion is recognized as one of the most destructive forms of soil degradation in arid and semi-arid regions, posing a serious threat to natural resources, agriculture, and human settlements (6, 14). This process intensifies in environments characterized by sparse vegetation, low precipitation, and strong winds, leading to the detachment, transport, and deposition of soil particles (7, 14). In Iran, where nearly two-thirds of the land area lies within arid and semi-arid zones and about 45 million hectares are classified as deserts, wind erosion is one of the primary causes of soil and natural resource degradation (8).

Eastern Isfahan is considered a major center of wind erosion and a significant source of dust storms in central Iran due to its geographic location and harsh climatic conditions. The region receives less than 50 mm of annual rainfall and has extremely limited natural vegetation cover. Human activities such as unsustainable farming practices, intensive gypsum and sand mining, and excessive exploitation of water

resources have further accelerated the erosion process (Meshkout et al., 2005; Ahmadi et al., 2004).

Wind erosion is a complex phenomenon influenced by two main groups of factors: intrinsic soil properties (erodibility) and wind characteristics (erosive power) (15, 18). Soil physical and chemical attributes, including texture, gravel content, moisture, organic matter, calcium, and magnesium, play a decisive role in soil erodibility (4, 10). External factors such as wind speed and direction control the detachment and movement of soil particles. Among surface characteristics, gravel cover has particular importance. By reducing direct wind-soil contact, lowering shear stress, and increasing surface roughness, gravel cover can significantly reduce erosion (6). Several studies have shown that higher gravel cover markedly decreases soil loss due to wind erosion (1, 11).

From a management perspective, understanding the processes that drive wind erosion and the role of variables such as gravel cover, soil physicochemical properties, and wind dynamics is essential for developing effective soil conservation and erosion

control strategies. Laboratory simulators such as wind tunnels provide valuable tools for examining soil responses under controlled and repeatable conditions (5, 19). These devices enable the measurement of critical parameters such as threshold wind velocity and soil loss rate. Previous research has also highlighted the importance of soil properties such as particle composition, calcium carbonate, electrical conductivity, and organic carbon in determining soil susceptibility to wind erosion (Prasuhin, 2012; 20). Moreover, divalent cations such as calcium and magnesium have been shown to enhance soil particle cohesion and reduce erodibility (7, 17).

Given the climatic conditions of eastern Isfahan and its high vulnerability to wind erosion, studies that simultaneously examine intrinsic soil properties and surface factors such as gravel cover are particularly important. The present study was designed to evaluate the effects of soil physicochemical characteristics and gravel cover on wind erosion intensity in the soils of eastern Isfahan using wind tunnel experiments. The findings are expected to provide practical insights for sustainable desert land management, the development of erosion mitigation strategies, and the protection of soil and vegetation resources in arid and semi-arid regions. In addition, the results can serve as a basis for future research on wind erosion modeling and the potential impacts of climate change on soil dynamics.

MATERIALS AND METHODS

This research was carried out to examine the influence of soil properties and gravel cover on wind erosion intensity in eastern Isfahan. The study area lies within the central plateau of Iran, in the Zayandeh-Rud watershed, less than 20 km from the center of Isfahan. The region has an arid climate, with a mean annual precipitation of about 50 mm in the plains and up to 250 mm in the northern highlands (14).

A geomorphological map of the area was prepared, and based on it, nine land units were identified. These included young and mature alluvial fans, gypsum and sand mines, piedmont plains, agricultural land, playas, and alluvial plains. From each unit, three surface soil samples were collected from a depth of 0–7 cm, yielding a total of 27 samples. The samples were air-dried, sieved through a 2 mm mesh, and transported to the laboratory for physicochemical analyses.

The physical properties measured included gravel percentage, soil texture (hydrometer method), bulk density (clod method), and saturated moisture content. The chemical analyses included electrical conductivity (EC), soil pH, calcium, magnesium, sodium, potassium, calcium carbonate, sulfate, chloride, and organic carbon, all determined using standard laboratory procedures.

Wind erosion was simulated using the wind tunnel system at the field laboratory of Isfahan University of Technology. This tunnel can generate wind velocities ranging from 2 to 18 m/s at a height of 30 cm. Soil samples were tested under three gravel cover

conditions (control, 15%, and 30%) and three wind speed levels (threshold, twice the threshold, and four times the threshold). The experiments followed a completely randomized three-factor design, and the data were analyzed using analysis of variance (ANOVA) and multivariate regression.

Assessment of the Influence of Soil Physicochemical Properties on Wind Erodibility

Soil erodibility is influenced by a combination of physical and chemical properties that determine the soil's resistance to wind shear forces (14). In this study, a range of properties was measured, including gravel percentage, soil texture, bulk density, saturated moisture content, electrical conductivity (EC), pH, calcium, magnesium, sodium, potassium, calcium carbonate, and organic carbon, and their relationship with wind erosion intensity was evaluated.

Analysis of soil texture indicated that finer particles (silt and clay) are more susceptible to wind detachment than coarser particles (sand) (7). Samples with higher clay content (e.g., barren piedmont plains) exhibited greater erodibility than sandy samples (e.g., sand mine soils). These findings are consistent with López Sánchez (11), who reported that fine-textured soils are more vulnerable to wind erosion.

Regarding gravel content, soils from mature alluvial fans and sand mines had higher surface gravel coverage, which played a significant role in reducing wind erosion (2). Conversely, playas and agricultural lands with low gravel coverage experienced the highest soil loss. Fryrear et al. (6) also reported that surface gravels increase surface roughness, reduce near-surface wind velocity, and significantly enhance soil resistance to erosion.

Saturated moisture content further contributed to soil stability. Samples with higher saturated moisture (e.g., agricultural alluvial soils) showed greater resistance to wind erosion, consistent with Armbrust (1), who noted that higher soil moisture increases particle cohesion and reduces erosion.

Among chemical properties, soils with higher EC (e.g., playas with sparse cover) were more prone to degradation, supporting Zhao and Pei (21), who reported that high salinity weakens soil structure and reduces resistance to wind forces. Analysis of soil cations revealed that higher calcium and magnesium levels, which promote particle flocculation, reduced erodibility. Soils with higher calcium content, such as mature alluvial fans, exhibited greater stability. Multivariate regression confirmed that calcium, magnesium, potassium, and calcium carbonate were the most influential variables predicting soil resistance to wind erosion. These findings highlight the potential role of soil amendments in desertification control and the stabilization of arid soils.

Overall, this section emphasizes the importance of carefully studying soil physicochemical properties for natural resource management and wind erosion control. In addition to surface measures such as gravel

cover, improving intrinsic soil properties is critical for achieving long-term soil resistance to erosion.

Evaluation of Gravel Cover in Reducing Wind Erosion under Different Wind Speeds

Surface gravel cover is one of the most effective methods for reducing wind erosion. Gravel acts as a physical barrier to wind shear, reducing wind speed at the soil surface and preventing particle detachment (11). In this study, three levels of gravel cover were tested: bare soil (control), 15%, and 30%.

Results showed that increasing gravel cover significantly reduced soil loss. At threshold wind speeds, bare soil samples experienced the highest losses, while samples with 30% gravel cover showed the lowest losses. These findings are consistent with Armbrust (1) and Fryrear et al. (6), who reported that increased gravel cover reduces wind erosion. For example, at threshold wind speed, soil loss in playas without gravel reached 9200 g/m², whereas soil with 30% gravel cover lost only about 6300 g/m². This demonstrates the stabilizing role of surface gravels in desert soils.

A similar pattern was observed at higher wind speeds (2× and 4× threshold). In all cases, increasing gravel cover significantly reduced erosion. For example, in young alluvial fans at four times the threshold wind speed, soil loss decreased from 449 g in bare plots (30 × 30 cm) to 329 g with 30% gravel cover. While the magnitude of reduction varied across geomorphological units depending on inherent soil characteristics, the overall trend was consistent.

The protective effect of gravel cover is particularly important under high wind speeds. As shown by López Sánchez (11) and Zhao et al. (20), soil loss typically increases exponentially with wind speed; however, surface gravels can substantially mitigate this effect. Data from the experiments indicated that the reduction effect of gravel was even more pronounced at higher wind speeds. Gravels disrupt airflow, increase surface roughness, and dissipate wind energy near the ground, reducing particle detachment forces.

The effectiveness of gravel cover also depends on the uniformity of distribution, particle size, and surface arrangement. In this study, gravels of approximately 1.5 cm diameter were evenly distributed to maintain standardized laboratory conditions.

Statistical analysis confirmed the significance of gravel cover. A three-way ANOVA (landform × wind speed × gravel cover) showed that gravel cover alone explained a considerable portion of the variance in soil loss ($p < 0.001$; $\eta^2 = 0.42$). These results are consistent with previous studies (7, 16) emphasizing the importance of surface covers in controlling wind erosion.

In conclusion, gravel cover should be prioritized in wind erosion control programs in arid regions. It is a cost-effective, natural, and efficient method for stabilizing soils, particularly in areas such as eastern Isfahan, where wind erosion is severe and vegetation is

sparse. Overall, the findings confirm that gravel cover effectively reduces soil loss across different wind speeds and plays a critical role in desert land management and dust mitigation.

Assessment of the Combined Effect of Wind Speed and Gravel Cover on Soil Loss Across Different Geomorphological Units

Geomorphological characteristics, including landform type, soil texture, surface cover, and chemical properties, directly influence the intensity of wind erosion (7, 21). In this study, the simultaneous effects of wind speed and gravel cover on soil loss were evaluated across nine geomorphological units: young, moderately developed, and mature alluvial fans; gypsum and sand mines; agricultural lands; piedmont plains; playas; and alluvial plains. Results indicated that each geomorphological unit responded differently to the combined influence of wind speed and gravel cover.

Under bare soil conditions (control), the highest soil loss occurred in playas with sparse cover, reaching 9221 g/m² at the threshold wind speed. In contrast, agricultural alluvial plains exhibited the lowest soil loss at 1388 g/m². These findings highlight the critical role of landform type and soil physicochemical properties in soil resistance to erosion.

Increasing gravel cover to 15% and 30% reduced soil loss in all geomorphological units, although the magnitude of reduction varied by landform type. For instance, in playas with 30% gravel cover, soil loss decreased to 5355 g/m²—a substantial reduction compared to bare soil. A similar reduction was observed in agricultural alluvial plains, where soil loss dropped to 967 g/m².

Higher wind speeds (2× and 4× threshold) increased soil loss across all landforms. Vulnerable units such as gypsum and sand mines and playas showed more pronounced increases. For example, at four times the threshold wind speed in gypsum mines without gravel cover, soil loss reached 850 g in a 30 × 30 cm plot (approximately 9444 g/m²). With 30% gravel cover, this decreased to about 6100 g/m².

Comparative analysis revealed that mature alluvial fans and alluvial plains, due to specific physical characteristics such as high natural gravel content, higher bulk density, and suitable saturated moisture levels, exhibited greater resistance to wind erosion (2, 11). Conversely, agricultural lands and mines, with finer-textured soils and reduced surface cover, were more susceptible to erosion.

Three-way ANOVA showed that the interaction between landform type and wind speed was significant ($p < 0.01$; $\eta^2 = 0.19$), and the interaction between wind speed and gravel cover was highly significant ($p < 0.001$; $\eta^2 = 0.42$). These findings emphasize the importance of considering surface and climatic characteristics for sustainable soil management.

From a management perspective, these results indicate that sensitive geomorphological units, such as playas

and mines, require targeted protective measures. Implementing gravel cover at adequate densities can substantially reduce wind erosion in these areas. In agricultural lands, protective measures such as mulching or increasing vegetation cover, in combination with gravel application, are recommended (16, 22).

Moreover, understanding the spatial and temporal patterns of erosion across geomorphological units is crucial for designing dust mitigation programs and maintaining soil quality. This study showed that, under typical wind speeds in eastern Isfahan (4 m/s) and frequent dust storms, attention to the distribution of vulnerable landforms is essential (21).

The findings also suggest that effective desert land management requires more than just vegetation cover; soil surface management through gravel stabilization or resistant mulches can be highly effective in controlling erosion (7). Ultimately, integrating these results with climatic data and geomorphological maps can form the basis for local and regional wind erosion sensitivity maps, identifying priority areas for conservation and guiding resource allocation for sand and dust stabilization projects.

DISCUSSION

The findings of this study indicate that soil physicochemical properties, along with the extent of surface gravel cover, play a crucial role in determining soil stability against wind erosion. Characteristics such as gravel percentage, soil texture, bulk density, saturated moisture content, electrical conductivity (EC), pH, and the concentrations of calcium and magnesium ions each influence the soil's susceptibility to particle detachment by wind (14). This research demonstrated that increasing surface gravel cover significantly reduces wind erosion intensity. This finding aligns with previous studies showing that gravel cover acts as a physical barrier, increases surface roughness, reduces wind speed at the soil interface, and decreases the effective shear force (11). Notably, this effect is more pronounced at higher wind speeds, indicating the critical role of gravel cover in controlling erosion during severe storms.

Soil physical properties also influenced wind erosion. Soils with higher clay and silt contents, such as agricultural lands on piedmont plains, were more sensitive to erosion. These results are consistent with reports by Gomez et al. (7) and Zhao & Pei (21), which identified fine-textured soils as more prone to particle detachment by wind. Regarding chemical properties, higher calcium and magnesium concentrations promoted flocculation of soil particles, thereby enhancing soil stability (2, 21). In this study, samples from mature alluvial fans and alluvial plains with high calcium carbonate content exhibited greater resistance to erosion. Conversely, soils with high salinity (high EC), particularly in playa sites, displayed reduced resistance and increased erosion. This finding is consistent with Zhao et al. (20), who noted that high

soil salinity can degrade soil structure and increase susceptibility to wind erosion.

The interaction between soil physical and chemical properties was also evident. For example, even in soils with a high proportion of coarse particles (sand), if the soil structure was weakened due to high salinity or low calcium content, wind erosion remained substantial. This observation highlights the importance of a comprehensive, integrated assessment of soil properties when analyzing wind erosion. From a management perspective, these findings underscore the need to simultaneously improve inherent soil properties (through enhancement of chemical and physical characteristics) and apply surface protection measures, such as gravel cover. Strategies such as increasing calcium in fine-textured and saline soils, applying mineral or gravel mulches, and planting erosion-resistant species can substantially improve the effectiveness of wind erosion control programs.

Comparative Evaluation of Landform Responses to Increased Wind Speed and Surface Management

Different geomorphological units exhibited varying responses to the combination of wind speed and gravel cover. Units with favorable physical characteristics, such as alluvial plains and mature alluvial fans, showed greater resistance to wind erosion compared to more vulnerable units, such as gypsum and sand mines and unvegetated playas. Under bare soil conditions and threshold wind speeds, playas with minimal gravel cover and high salinity exhibited the highest soil loss, while relatively resistant alluvial plains showed the lowest loss. These results are consistent with previous studies (Sterk, 16; Van Donk et al., 17), which emphasized the importance of landform type and surface characteristics in determining erosion intensity. At higher wind speeds (2× and 4× threshold), differences among units became more pronounced. Vulnerable soils, such as those in mines and playas, experienced exponential increases in erosion, whereas more resistant soils remained relatively stable. These findings highlight the importance of designing protective management strategies according to landform characteristics. Applying surface gravel cover (15% and 30%) significantly reduced soil loss across all units, though the degree of reduction depended on inherent soil properties. In highly sensitive areas, such as playas, even 30% gravel cover could not fully prevent severe erosion under high wind speeds. In contrast, in more resistant areas like alluvial plains, the same gravel cover substantially reduced soil loss.

From a practical standpoint, these results indicate that wind erosion management strategies should be tailored to the specific characteristics of each landform. For sensitive lands, a combination of interventions including gravel stabilization, planting drought- and wind-resistant species, and applying artificial or organic mulches is recommended. For more resistant lands, minimal gravel cover or vegetation management

may suffice. Moreover, considering the prevailing wind direction and intensity (northwest winds in eastern Isfahan) can significantly enhance the efficiency of protective measures. Aligning gravel cover along the dominant wind direction can greatly improve soil protection.

Ultimately, the findings emphasize that desertification control and dust mitigation programs should be implemented at a regional scale and based on landform-specific characteristics. Uniform approaches are unlikely to effectively protect all areas against wind erosion.

CONCLUSION

Based on statistical analyses obtained from multivariate regression at the threshold wind speed, the soil properties most influential on soil loss were calcium, magnesium, potassium, and calcium carbonate, with calcium and magnesium having the greatest impact. Since these two cations are key factors in soil particle flocculation (aggregation), their presence reduces soil erodibility. Conversely, as the percentage of gravel decreases, soil protection diminishes, the threshold wind speed for erosion decreases, and consequently, soil erodibility increases. Calcium carbonate was also identified as a critical factor affecting soil loss, indicating that in eastern Isfahan, higher lime content enhances soil aggregate stability and reduces soil loss.

It was also found that increasing surface gravel cover reduces wind erosion, while higher wind speeds increase it. The highest gravel percentage (75%) was observed in mature alluvial fans, whereas the lowest (3%) occurred in playas. These findings highlight the importance of considering gravel cover in controlling wind erosion. Given the sensitivity of soils and the wind-prone nature of the region, it is recommended that land surfaces maintain continuous cover and minimize exposure to erosive winds throughout the year. Relevant authorities, such as provincial offices, agricultural organizations, natural resources, and regional water authorities, should refrain from issuing permits that remove natural soil surface cover, such as gravel in alluvial fans and plains.

Wind erosion is a major challenge in arid and semi-arid regions, posing a serious threat to soil resources and the environment. This study demonstrated that wind erosion is influenced by multiple factors, including soil physical and chemical properties and surface cover, such as gravel. The study evaluated these factors across various geomorphological units in eastern Isfahan, showing that changes in soil properties and gravel cover can significantly reduce wind erosion. One key finding was that soils with higher clay and silt content, such as agricultural lands and piedmont plains, were more sensitive to wind erosion, particularly those with higher salinity. This aligns with previous studies indicating that fine-textured and saline soils are more susceptible to wind erosion. Therefore, in areas with fine-textured and

saline soils, corrective measures such as increasing calcium and magnesium content can substantially reduce wind erosion.

The results also highlighted that surface gravel percentage plays a key role in reducing wind erosion intensity. Gravel cover acts as a barrier, increases surface roughness, reduces wind speed near the soil surface, and prevents particle detachment. This effect was more pronounced at higher wind speeds, emphasizing the critical role of gravel cover in mitigating erosion during severe storms. In this study, increasing gravel cover from 15% to 30% significantly reduced soil loss, especially in sensitive geomorphological units like playas.

Comparing different geomorphological units showed that soils with favorable physical properties (e.g., alluvial plains and mature alluvial fans) were more resistant to wind erosion than more vulnerable units (e.g., mines and unvegetated playas). Specifically, at higher wind speeds, units with insufficient vegetation or gravel cover experienced a sharp increase in soil loss. These findings are consistent with previous studies showing that areas with weak or absent surface cover are more prone to erosion, particularly under dust storms and strong winds.

The interactive effect of wind speed and gravel cover on wind erosion was clearly observed. In all geomorphological units, increasing wind speed caused a significant increase in soil loss, but the increase was much more severe in vulnerable areas such as mines and playas. At higher wind speeds ($2\times$ and $4\times$ threshold), differences among units became more evident. In contrast, more resistant units, such as alluvial plains, remained relatively stable against wind erosion. This underscores the importance of considering local climatic and geomorphological conditions when designing wind erosion management strategies.

Statistical analyses, such as three-way ANOVA, also indicated that soil properties and surface cover interactively play an important role in controlling wind erosion. Regression analyses showed that calcium, magnesium, and calcium carbonate are the most significant predictors of soil resistance to wind erosion. These findings clearly demonstrate that integrated management of soil physicochemical properties along with surface protection can effectively reduce wind erosion and enhance the stability of desert soils against dust storms.

Based on these results, several management recommendations are proposed for reducing wind erosion in arid and semi-arid regions:

1. In fine-textured and saline soils, corrective techniques such as adding calcium, magnesium, or other minerals can enhance soil resistance.
2. Establishing surface gravel cover in vulnerable desert lands, especially in areas with high wind speeds, can significantly reduce wind erosion.

3. In regions exposed to high wind velocities, multiple protective measures—such as mulching, planting drought- and wind-resistant vegetation, and improving soil structure to prevent particle detachment—are necessary.

This study emphasizes that effective wind erosion control in arid and semi-arid regions requires regional-scale soil management strategies tailored to the specific characteristics of each landform and local climatic conditions. Finally, these findings can provide a foundation for future research on wind erosion modeling and assessing the impacts of climate change on soil dynamics.

Acknowledgments

The authors would like to thank their respective institution and colleagues for their support and assistance during the conduct of this study.

Financial Support

No financial support was received for this study.

Conflict of Interest

The authors declare that they have no conflict of interest.

Funding Declaration

No external funding was received for this study.

Ethics Declaration

Not applicable.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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