

Effectiveness of a Novel Biopolymer-Based Mulch in Reducing Particulate Emissions from Iron Ore Concentrate Piles Located in Arid Lands

Fatemeh Roustaei^{1, *}, Mohammad Khajeh Mehrizi², Hasan Akhiri³, Jafar Mahmoudi⁴

Receive: 2026/04/12

Accept: 2026/05/04

Abstract

In the mining and steel industry situated in arid lands, significant concentrations of particulate matter (PM) are emitted from raw material storage sites, particularly from iron ore piles and concentrate storage piles. In this study, the effectiveness of BDS mulches, a novel biopolymer-based mulch, was compared with slurry lime and sugarcane molasses as conventional compounds for covering iron concentrate storage piles to control wind erosion. The experiments were conducted using a factorial design within a randomized complete block design. BDS at concentrations of 1% and 2%, slurry lime at 10%, and molasses at 20% solution concentrations were prepared. Each treatment was sprayed onto three trays filled with concentrate. The prepared sample trays were subjected to wind erosion tests in a wind tunnel after 1, 2, and 3 weeks following preparation. Among the selected treatments, BDS at 2% (BDS2%) exhibited the highest efficiency, reducing wind erosion to 0.34 kg/m²/h compared to 2.1 kg/m²/h in the control treatment, and increasing the erosion threshold velocity to 54 km/h, whereas the control had a threshold of only 26 km/h. Slurry lime offered lower resistance to wind erosion, with an erosion rate of 1.8 kg/m²/h and a threshold velocity of 39.6 km/h. The effectiveness of molasses and BDS at 1% (BDS1%) was similar, with erosion rates of 1.1 and 1.2 kg/m²/h, and threshold velocities of 47.5 and 48.2 km/h, respectively. Moreover, the effectiveness of the mulches diminished over time, with erosion rates increasing by an average of 35–50% from week 1 to week 3. Considering the advantages of the new material—including environmental compatibility, no negative effects on pellet quality, and favorable efficiency in protecting against wind erosion—it can replace conventional compounds as a mulch for iron concentrate piles.

Keywords: Mulch, BDS, Wind Erosion, Threshold Velocity.

1. Department of Nature Engineering, Faculty of Agriculture & Natural Resources, Ardakan University, P.O. Box 184, Ardakan, Iran.

*Corresponding author. Email addresses: froustaei@ardakn.ac.ir (F.Roustaei), hassan.akhiri@gmail.com (H.Akhiri), jafarmahmoudi134@gmail.com (J.Mahmudi)

2. Department of textile engineering, Yazd University, Yazd, Iran.

3. Chadormalu Industrial Complex Research and Development, Chadormalu Mining and Industrial Company, Yazd, Iran. Department of Chemistry, Faculty of Science, Payam-e Nour University of Ardakan, Yazd, Iran.

4. Department of Chemistry, Faculty of Science, Payam-e Nour University of Ardakan, Yazd, Iran.

Introduction

Iron concentrate is one of the key products in the steel production chain. It is obtained from the processing of iron ore and contains a high percentage of iron (Ling et al., 2024). Owing to its high purity, this material plays a significant role in optimizing steelmaking processes and is primarily used in the production of pellets, sponge iron, and ultimately various types of steel. (Purohit et al., 2025). Iron concentrate stockpiles located in arid regions emit particles known as "fugitive dust," which can have adverse effects on workers' health and the surrounding environment (Žitnik and Topić, 2012, Susanto et al., 2024, dos Reis Lemos Fontana et al., 2025). The factors affecting wind-blown particles from material storage piles include wind speed and direction, pile shape, pile density, particle size, pile height, area of the pile exposed to wind, ambient atmospheric humidity percentage, and pile surface characteristics (Hassanvand et al., 2012). The lower the humidity, the greater the effect of wind force on the piles. Considering the height and wind-exposed area of the pile is essential for optimizing pile formation in raw material storage. (Badr and Harion, 2007). These physical factors directly govern the rate and intensity of dust emissions, which ultimately determine the scale of their environmental and health consequences. In arid regions, where climatic conditions exacerbate dust generation, the consequences of wind erosion are particularly severe. Controlling wind erosion in these regions is crucial not only for economic efficiency but, more importantly, for reducing negative impacts on surrounding ecosystems, soil quality, and human health. Moreover, the Environmental Protection Organization of Iran has adopted EPA standards as its objective to minimize the adverse effects of pollutants on the surrounding environment and human health, and has mandated that all industrial units comply with these standards. (Taghizadeh et al., 2023).

Among the various techniques available for erosion control, mulching has long been recognized as a reliable and effective method. Mulching is a well-established approach in soil preservation and erosion control; it creates a protective layer on the ground and conserves the soil surface against agents such as wind and rainfall (Subudhi et al., 2025, Ahmad et al., 2022).

Polymers can be considered appropriate materials for stabilizing iron concentrate particles. A prominent feature of polymers is their ability to form a surface network, thereby bridging particles (Markiewicz et al., 2024) and enhancing their stability by connecting them (Wang et al., 2023).

The effectiveness of biopolymers as wind erosion control agents has been demonstrated in natural environments such as soils and sand dunes (Dandin et al., 2025, Feizi et al., 2025). For instance Ayeldeen et al. (2018) demonstrated the performance of biopolymers such as carrageenan and modified starch at concentrations of 0.5% and 0.75% in reducing soil wind erosion. Similar research extends to other biopolymers, including polyacrylamide acid and gelatin (Hu et al., 2020), xanthan and guar gum (Kumar et al., 2025, Kumar et al., 2024), sodium alginate and pectin (Lemboye et al., 2021), which have confirmed their effectiveness in improving soil cohesion and surface resistance to aeolian processes.

While numerous studies have focused on wind erosion control for natural soils, research on stabilizing industrial stockpiles, such as iron concentrate, remains limited. This is a critical gap, as the loss of these valuable materials not only causes environmental and health problems but also leads to significant economic losses. Among these studies, the work of Hassanvand et al. (2012) can be mentioned, which demonstrated the efficiency of polylactic acid (0.25%) as a dust particle stabilizer in comparison to slurry lime (2%) for stabilizing the upper layer of the pile. However, that study focused primarily on the initial effectiveness of

the treatments and did not address the durability and longevity of these coatings over time. The most important materials used as mulches for stabilizing iron concentrate piles in Iran include lime, molasses, and bentonite. The existence of issues such as health and environmental problems, as well as challenges associated with their use, has led employers to seek alternative materials. Despite the widespread use of these traditional materials in Iran, no quantitative and systematic evaluation has been conducted to assess the performance of molasses and lime slurry compared to novel biopolymers on iron concentrate. In other words, this study is the first to directly compare the performance of conventional mulches with a modern, environmentally friendly alternative on this specific industrial substrate.

The novel mulch investigated in this study is designated BDS (Biopolymer Dust Suppression), which is based on cellulose biopolymers. This odorless, powdery material poses no health or environmental concerns. BDS is sprayed onto the surface after dissolution in water to form a white, wind-erosion-resistant layer. The hypothesis is that cellulose-based biopolymers can form a durable yet non-interfering surface crust on iron concentrate piles, thereby addressing the limitations of conventional mulches such as lime and molasses.

Accordingly, the present study was conducted with the following objectives:

- 1- To compare molasses and slurry lime as traditional mulches with BDS at two concentrations (1% and 2%) as novel mulches for controlling wind erosion on iron concentrate piles.
- 2- To determine and compare the threshold wind speed for wind erosion across different treatments.
- 3- To evaluate the effectiveness and durability of the mulches over time.
- 4- To investigate the impact of BDS mulch on the subsequent industrial processing (pelletization) of the iron concentrate.

Materials and Methods

Study area

The study area is located at the Chadormaloo Industrial Complex, which is part of the Aqda district, Ardakan city. This area is situated at the geographical coordinates of 32°23'25"N and 53°45'5"E. The elevation of the area above mean sea level is 1,027 meters. Based on the De Martonne climate classification, this region is classified as arid.

The summer season accounts for 60% of annual winds, while the winter season accounts for 54%, representing the highest and lowest percentages of wind occurrence, respectively, in terms of both direction and speed. During the summer season, the prevailing wind blows from the northeast. Among these, 14% are light to moderate winds with speeds ranging from 7 to 22 km/h, 6% are northerly winds with speeds of 22 to 30 km/h, and 2% are strong winds.

Four treatments were prepared and sprayed onto the surface of trays filled with iron concentrate: BDS at concentrations of 1% and 2% (w/w), lime at 10% (w/w), and molasses at 20% (w/w). The concentrations of molasses and lime were selected based on current practices at the Chadormaloo Industrial Complex and other steel industries in Iran, while the BDS concentrations were selected based on what could be considered optimal concentrations according to experimental studies. Additionally, thirty-six galvanized trays, each measuring 5 × 30 × 103 cm, were used to hold the concentrate for wind erosion and other tests.

Molasses

Sugar cane molasses is a viscous byproduct derived from the processing of sugar cane into sugar (Olbrich, 2006; Geremew Kassa et al., 2024). During the sugar-making process, the juice extracted from sugar cane is boiled until the sugars crystallize and precipitate out. The syrup remaining after crystallization is referred to as molasses (Bethlehem, 2015).

The 20% concentration represents the standard industrial practice currently employed

at the Chadormalu Industrial Complex and other steel facilities in Iran. This concentration has been empirically optimized by industry operators to achieve sufficient viscosity (200–800 cP) for surface adhesion while remaining economically viable and operationally manageable. Other characteristics, such as resource availability, economic price, and the lack of need for special preparation due to its liquid nature, have led to its widespread use in Iran for stabilizing concentrate piles. However, its highly unpleasant odor, mold growth in storage tanks, and corrosion of conveying systems have prompted users to seek alternatives.

Lime

Slurry lime is an aqueous solution of calcium hydroxide ($\text{Ca}(\text{OH})_2$) and is typically produced by dissolving hydrated lime in water. Its advantages—including being economical, odorless, and readily available—have led to its use as a mulch in some steel industries. However, challenges such as rapid hardening, fast settling in storage tanks, and the presence of coarse particles that clog spray nozzles complicate its application. The 10% concentration reflects the standard industrial formulation used for dust suppression in Iranian steel industries. This concentration balances two competing requirements: sufficient calcium hydroxide content to form a cohesive crust upon drying, and adequate fluidity to ensure uniform spray application.

BDS

BDS was selected for this study based on its unique physicochemical properties, which make it particularly suitable for industrial dust suppression applications. Unlike traditional biopolymers such as guar gum, xanthan gum, or starch-based products that have been extensively studied for soil stabilization (Kumar et al., 2024; Lemboye et al., 2021), BDS is based on cellulose—an abundant, renewable, and biodegradable linear

polysaccharide. The molecular structure of cellulose, characterized by extensive hydrogen bonding capabilities, enables it to form strong adhesive bridges between fine iron concentrate particles (Wang et al., 2023). Additionally, the incorporation of micronized calcium carbonate (49.13% CaO as shown in Table 1) serves a dual purpose: it enhances the mechanical strength of the surface crust and provides a white coloration that reflects solar radiation, thereby potentially reducing thermal degradation of the biopolymer matrix.

Preliminary laboratory trials indicated that concentrations below 1% failed to form a continuous protective layer on the concentrate surface, while concentrations above 2% resulted in excessive viscosity, leading to non-uniform application and deep cracking upon drying. Therefore, the selection of BDS and its concentrations (1% and 2%) was hypothesis-driven, aiming to evaluate the dose-response relationship of a cellulose-based biopolymer specifically formulated for industrial dust control. The compositional analysis of BDS is presented in Table 1.

Table 1. Biopolymer Dust Suppression analysis

Elements	Percentage ratio(%)
SiO ₂	1.26
Al ₂ O ₃	0.059
Fe ₂ O ₃	0.054
MnO	n.d
TiO ₂	n.d
CaO	49.13
MgO	0.38
Na ₂ O	0.25
K ₂ O	0.10
P ₂ O ₅	n.d
SO ₃	<0.1
L.O.I	48.09

Experimental Design:

A factorial experiment based on a randomized complete block design (RCBD) was employed to evaluate the effects of different mulches and their concentrations on

wind erosion control over time. The experimental factors and their corresponding levels were as follows:

Factor 1: Mulch type at four levels:

- (i) control (no mulch),
- (ii) (ii) slurry lime (10% w/w),
- (iii) (iii) sugarcane molasses (20% w/w), and
- (iv) (iv) BDS biopolymer at two concentrations (1% and 2% w/w).

Factor 2: Time after application at three levels: 1 week, 2 weeks, and 3 weeks.

The response variables measured were:

- (i) wind erosion rate (kg/m²/h),
- (ii) (ii) threshold wind velocity (km/h),
- (iii) (iii) aggregate stability (mean weight diameter, MWD), and
- (iv) (iv) surface penetration resistance (kg/cm²).

The RCBD was implemented to account for variability in environmental conditions within the wind tunnel facility, such as slight differences in temperature, humidity, or airflow uniformity across experimental runs. Three blocks were defined based on the physical position of sample trays in the wind tunnel, and treatments were randomly assigned within each block to ensure independence of observations and to reduce uncontrolled error. Each treatment combination (mulch type × time) was replicated three times, resulting in a total of 36 experimental units (4 mulch types × 3 time levels × 3 replicates). The randomization procedure was performed using a random number generator to ensure unbiased assignment of treatments to trays within each block.

This design allows for the simultaneous assessment of the main effects of mulch type and time, as well as their potential interaction, on the erosion-related response variables

Wind Tunnel Experiments:

A wind tunnel was used to compare the efficiency of different mulches in terms of wind entrainment and also to compare the threshold velocity of particles covered by them. Wind

tunnels are specialized facilities for studying wind erosion, offering a controlled environment to test variables and enhance understanding of erosion processes (Erci et al., 2021; Rostami et al., 2025).

Tests were conducted under ambient laboratory conditions, with temperatures ranging from 25 to 30°C and relative humidity between 30% and 40%. All samples within each time period (1, 2, and 3 weeks) were tested on the same day to minimize environmental variability within each time point.

The wind speed applied to the samples was controlled using an anemometer at 15-minute intervals. The maximum wind speed generated by the device was 55 km/h. To measure the erosion rate for each sample, the sample was weighed before and after the test, and the erosion rate per unit area was calculated.

To determine the threshold wind velocity, galvanized trays holding thoroughly dried concentrate subjected to various treatments were tested in a controlled wind tunnel. Wind speed was gradually increased, and the critical wind speed at which particle movement commenced was recorded as the threshold wind speed (Ekhtesasi and Zare Chahouki, 2016).

Aggregate Stability Analysis:

To evaluate the efficiency of the studied soil covers in binding particles and forming and stabilizing aggregates, a stability test of the formed aggregates was performed. For this purpose, at the end of each test time, the samples were passed through a series of sieves (250, 160, 125, 90, 63, and 45 μm) using a rotating sieve machine at 50 rpm for 5 minutes. Finally, after separating the concentrate particles, the mean weight diameter (MWD) was calculated as the aggregate stability index according to the following equation (Eq. 1) (Bhattacharya et al., 2021).

$$\text{MWD} = \sum_{i=1}^n w_i \bar{d}_i \quad (1)$$

Where w_i is the weight (or proportion) of particles in the i th size category, \bar{d}_i is the mean diameter of particles in the i th size category and n is the total number of size categories.

Cone Penetration Test Measurements:

Penetration resistance of the surface soil under different treatments was measured using a cone penetration tester (CPT). This method involves placing a cone on the soil surface and pressing it downward vertically at a moderate speed (approximately 1.5 to 2.5 cm/s) (Gao et al., 2016).

The accuracy of the CPT depends on the cross-sectional area (10 or 15 cm²) and the diameter (3.6 to 4.4 cm). This instrument measures penetration soil strength ranging from 0 to 2.5 kg/cm².

Pellet Preparation and Testing

The properties of the pellets were studied in terms of drop number (Tavares et al., 2025) and green crushing strength (GCS) (Sagar et al., 2025). To produce pellets, 10 kg of concentrate mixture with BDS mulch and molasses (taken from galvanized trays after the aforementioned tests) was combined with 0.9% bentonite and water. Pellets were prepared using a laboratory pelletizer disc.

Drop number was determined using 10 wet pellets of 12 mm, separated by a sieve with a

size range of 5–10 mm. Pellets were dropped from a height of 46 cm onto a steel plate, and this process was repeated until cracks were observed on the pellets. For GCS, wet strength was measured by placing ten raw pellets in the device at a pressure rate of 40 mm/min and averaging the results. Dry strength was measured similarly after drying the pellets in an oven at 105°C for 24 hours.

RESULTS

General characteristics of iron concentrate

According to Table 2, the concentrate used in the tests had an iron content of 66.48% (TFe) and a Blaine specific surface area of 1782 cm²/g, indicating a fine-grained material. Particle size distribution analysis showed that approximately 70% of the particles had diameters between 90 and 120 μm, while only about 7% were 45 μm or smaller (Figure 1). Impurity levels were measured as follows: SiO₂ at 3.7%, Al₂O₃ at 0.72%, MgO at 0.97%, and CaO at 0.92%.

Table 2. Characteristics of the concentrate used in the research (Chadormlu Central Laboratory)

T Fe	Fe O	Bl aine	Si O ₂	Al ₂ O ₃	C a O	M g O	P	M n O	Ti O ₂
66	25	17	3.	0.7	0.	0.	0.	0.	0.
.4	.4	82	7	2	92	97	09	06	3
8	1						2		

Particle Size Distribution (%)

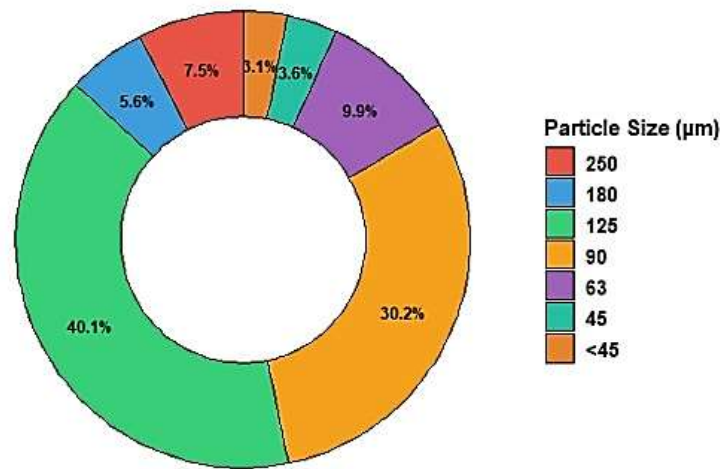


Figure1. Particle size distribution in the iron ore piles, Chadormalu mining and industrial Company

Wind erosion threshold velocity

A comparison of the threshold wind speeds for uncoated trays and mulched trays is presented in Figure 2. The lowest threshold speed was recorded for the uncoated concentrate at 26 km/h, followed by lime at 39.6 km/h. Similar efficacy was demonstrated by the molasses and BDS 1% treatments,

increasing the threshold velocity to 47.5 km/h (an 82.7% increase) and 48.2 km/h (an 85.4% increase), respectively. The highest threshold velocity was observed for BDS at 2%, reaching 54 km/h, which represents a 107.7% increase over the control.)

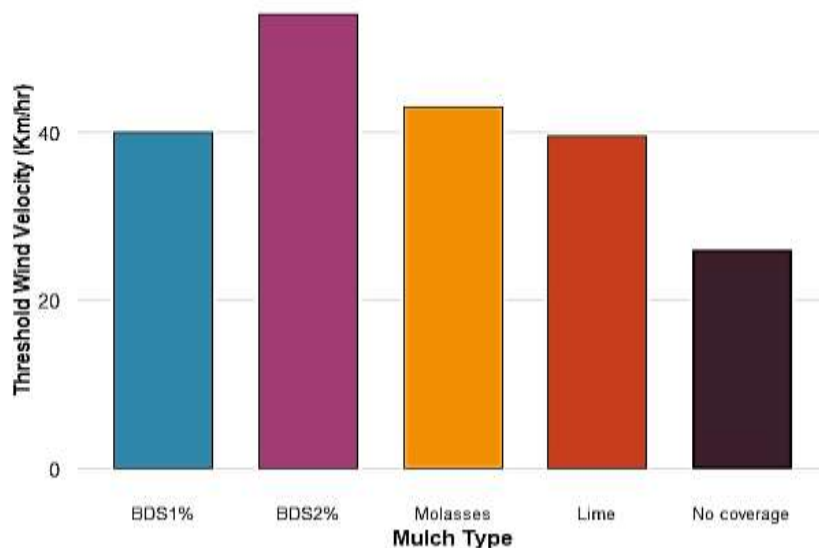


Figure 2. Wind erosion threshold speed comparison in different treatments

Wind erosion rate

The effect of crusts on wind erosion was examined by a one-way ANOVA (Table 3). The results showed significant differences

between the groups ($F(3, 20) = 5.53$, $p = 0.004$, $\eta^2 = 0.34$). The between-groups sum of squares was 52838.02 ($df = 3$), and the within-groups sum of squares was 101835.4 ($df = 20$). The effect size (η^2) indicated that the 34% of the

variance in soil erosion can be explained by soil cover type, that is a considerable effect size according to Cohen's guidelines.

Table 3. ANOVA of the mulch effects on wind erosion

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	52838.02	3	17612.67	5.534	0.004
Within Groups	101835.4	32	3182.356		
Total	154673.4	35			

The Tukey test was conducted for revealing the group's relationship (figure 3). Tukey tests confirmed that BDS2% and molasses significantly reduced erosion compared to lime treatment ($p < 0.05$), while the difference between molasses and BDS1% was not statistically significant (Figure 3).

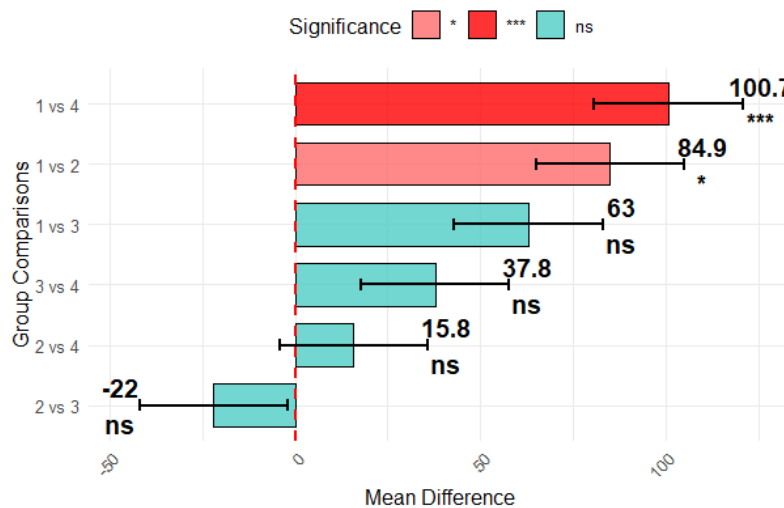


Figure 3. Pairwise mean difference in wind erosion rates between groups) G1 is lime treatment, G2 is molasses treatment, G3 is BDS1% treatment, and G4 is BDS2% treatment) .

Aggregate Stability Test in Different Soil Covers

According to ANOVA results, no statistically significant differences between the groups ($F(3, 20) = 0.291$, $p = 0.831$, $\eta^2 = 0.042$). The between-groups sum of squares was 0.411 ($df = 3$), and the within-groups sum of squares was 9.423 ($df = 20$). The effect size (η^2) indicated that only 4.2% of the variance in soil aggregate stability was explained by soil cover type, suggesting a negligible practical significance (Table 4).

Table 4. ANOVA of the mulch effects on soil aggregate stability

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.411	3	0.137	0.291	0.831
Within Groups	9.423	20	0.471		
Total	9.835	23			

The effect of different mulches on compressive strength

According to table 5 significant differences between the means of different groups were observed on compressive strength variable ($F(3, 31) = 3.651$, $p = 0.023$). Post-hoc comparisons demonstrated that there is a statistically significant difference in the mean

values between molasses and BDS1% ($p < 0.05$). In contrast, other comparisons between the groups were not significant (figure 4).

Table 5. ANOVA of the mulch effect on compressive strength

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5.024	3	1.675	3.651	.023
Within Groups	14.219	31	.459		
Total	19.243	34			

Cone penetration resistance values varied considerably among treatments. Molasses-treated samples exhibited the highest surface resistance ($1.85 \pm 0.21 \text{ kg/cm}^2$), followed by lime ($1.42 \pm 0.18 \text{ kg/cm}^2$), BDS1% ($0.93 \pm 0.12 \text{ kg/cm}^2$), and BDS2% ($0.68 \pm 0.09 \text{ kg/cm}^2$). Despite its lower penetration resistance, BDS2% maintained surface integrity with crack density of 2.3 cracks/ m^2 and mean crack width of 0.5 mm, compared to molasses which developed crack density of 18.7 cracks/ m^2 with mean crack width of 4.2 mm (Figure 5).

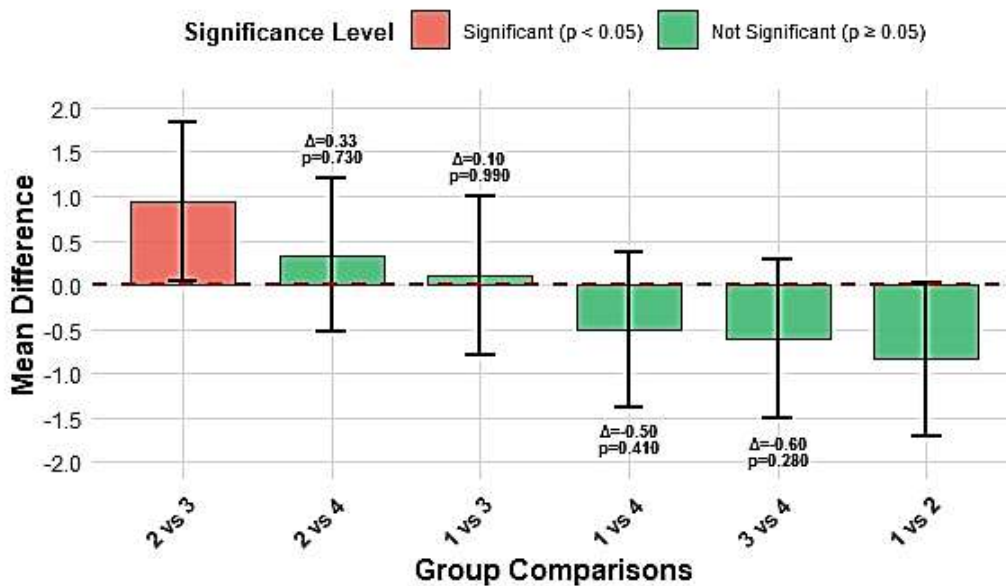


Figure 4. Pairwise mean difference in compressive strength rates between groups (G1 is lime treatment, G2 is molasses treatment, G3 is BDS1% treatment, and G4 is BDS2% treatment).

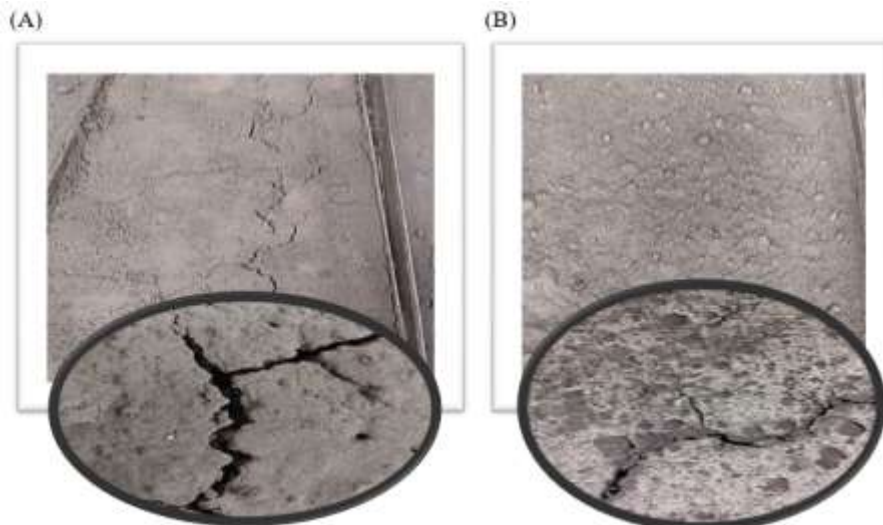


Figure 5. Concentrate sample coated with molasses (A) and BDS2% (B)

Temporal changes in wind erosion rate

Wind erosion rates increased progressively for all treatments over the three-week period (Figure 6). For lime-treated samples, erosion rates increased from 1.4 kg/m²/h (week 1) to 1.8 kg/m²/h (week 2) and 2.0 kg/m²/h (week 3), representing a 42.9% increase from week 1 to week 3. Molasses showed increases from 0.8 kg/m²/h (week 1) to 1.0 kg/m²/h (week 2) and

1.2 kg/m²/h (week 3), corresponding to a 50.0% increase. BDS at 1% increased from 0.9 kg/m²/h (week 1) to 1.1 kg/m²/h (week 2) and 1.3 kg/m²/h (week 3), representing a 44.4% increase. BDS at 2% increased from 0.22 kg/m²/h (week 1) to 0.30 kg/m²/h (week 2) and 0.38 kg/m²/h (week 3), corresponding to a 72.7% increase in relative terms, while maintaining the lowest absolute values at all time points.

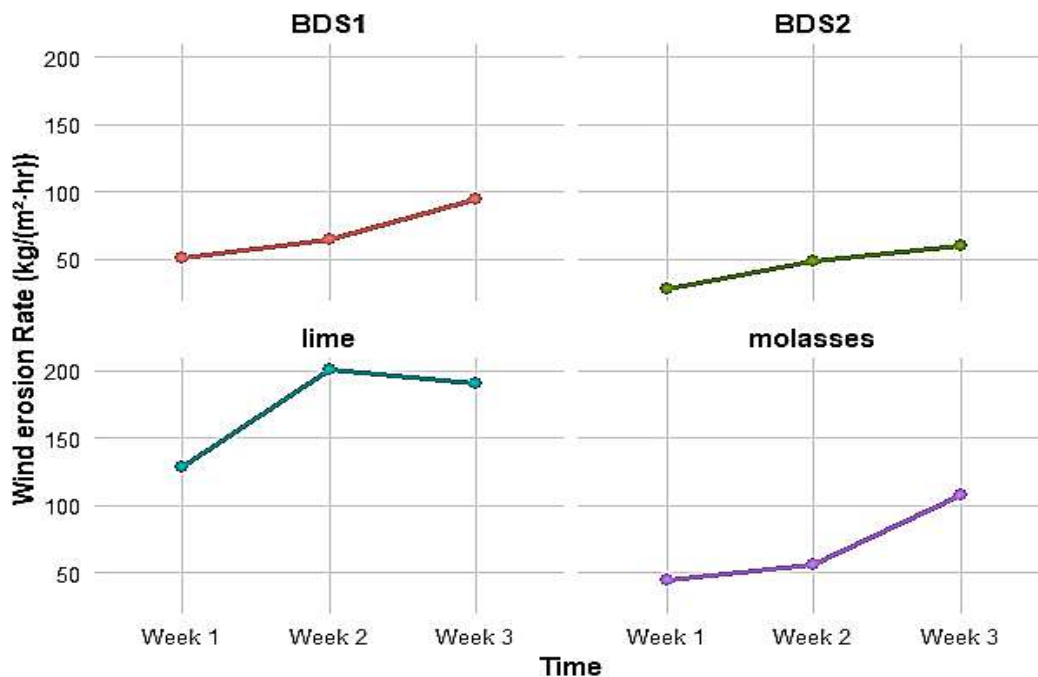


Figure 6. Comparison of wind erosion rate over three weeks among four Treatments: Lime, Molasses, BDS1%, and BDS2%

Investigating the effect of mulch on the physical properties of pellets

Pellets produced from concentrate treated with BDS2% and molasses both met industrial quality standards (Table 6). Moisture content was 9.3% for BDS2% and 8.3% for molasses. Drop number values were 2 for BDS2% and 2.2 for molasses, with no significant difference between treatments (t-test, $p = 0.342$). Green compressive strength (GCS) was 3.5 kg/pellet for BDS2% and 6.3 kg/pellet for molasses with the difference being statistically significant (t-test, $p = 0.008$). Both values exceed the

industrial minimum requirement of 2.0 kg/pellet.

Table 6. The effect of molasses and biopolymer mulches on the physical properties of pellets (Normal pellet count, very small size)

Sample	Moisture	Drop	GCS
BDS2%	9.3	2	3.5
Molasses	8.3	2.2	6.3

Discussion

The comparison of the effectiveness of different mulches (lime, molasses, and biopolymer at two concentrations) showed that

BDS at 2% was the most effective in controlling wind erosion on iron concentrate piles. This mulch, with advantages such as being environmentally friendly and user-friendly, binds with the concentrate particles to a penetrating depth, thereby increasing the threshold wind velocity required to initiate particle movement.

Lime in this study showed the weakest performance among all treatments, with only 14% erosion reduction and a 52% increase in threshold velocity (from 26 to 39.6 km/h). This finding is in notable contrast with Hassanvand et al. (2012), who reported 99.5% dust reduction using quicklime at 2% concentration on iron ore piles. Several factors may explain this discrepancy.

First, the study by Hassanvand et al. (2012) only evaluated the immediate effectiveness of treatments without assessing their performance over time, whereas our study demonstrates a 42.9% performance decline for lime from week 1 to week 3. Second, the brittle nature of the crust formed by lime, as confirmed by Emami et al. (2021) and Shojaei et al. (2021), leads to rapid cracking on the non-porous iron concentrate substrate, significantly reducing its effectiveness. Third, Komaei et al. (2023), in their study on the durability of cementitious crusts, highlighted the vulnerability of brittle crusts to environmental stresses, which aligns perfectly with our observations.

The 52% increase in threshold velocity achieved by lime in our study, while modest, indicates that even this poorly performing treatment provides some initial protection. However, the combination of brittleness, cracking, and rapid performance decline renders lime unsuitable as a long-term solution for iron concentrate stockpiles, particularly when compared to alternative treatments.

Molasses at 20% concentration demonstrated intermediate performance, with an 83% increase in threshold velocity (from 26 to 47.5 km/h) and 48% erosion reduction. These results can be evaluated in comparison with

Nikseresht et al. (2020), who studied molasses on desert soil over 14 days. They reported that molasses, as a microbial growth substrate, increased the surface stability of soil but also confirmed that its effectiveness declines over time due to microbial degradation, which aligns with our observation of 50% performance loss from week 1 to week 3.

Liu et al. (2022) reported that molasses acts through the formation of colloidal bonds that increase adhesion between particles, a mechanism consistent with our findings. However, our study reveals that the formation of deep cracks on molasses-treated surfaces (Figure 5A) is a critical limiting factor that creates preferential pathways for wind erosion. Wang et al. (2024) also investigated molasses as a dust suppressant and reported increased particle adhesion but did not address the issue of surface cracking.

The 48% erosion reduction achieved by molasses, while substantially lower than that of BDS at 2%, still represents meaningful protection. However, this must be weighed against its operational disadvantages, including unpleasant odor, mold growth in storage tanks, and equipment corrosion, as documented by Olbrich (2006) and confirmed by industrial practice in Iran.

BDS at 2% concentration demonstrated the best performance in this study, with a 108% increase in threshold velocity (from 26 to 54 km/h) and 84% erosion reduction. These results are comparable with those of previous studies on biopolymer applications for erosion control. Ayeldeen et al. (2018) investigated modified starch at 0.75% on sandy soil and reported a 59.5% increase in threshold velocity, which is lower than the performance of BDS at 2%. This difference can be attributed to the higher concentration (2% vs. 0.75%) and the cellulose-based structure of BDS, which has a greater capacity to form strong hydrogen bonds with concentrate particles, as described by Wang et al. (2023).

Lemboye et al. (2021) used xanthan gum at 1% on dune sand and reported a 184% increase in threshold velocity, which is higher than the value obtained in our study. This difference is attributable to substrate characteristics: dune sand possesses larger, porous particles that allow deeper polymer penetration, whereas iron concentrate has low porosity, limiting biopolymer infiltration to surface layers.

Feizi et al. (2019) used PVA on sandy loam and reported 85% erosion reduction and a 118% increase in threshold velocity, which closely matches the performance of BDS at 2% (84% reduction, 108% increase). He et al. (2008) reported 76% erosion reduction with PAM, and Hassanvand et al. (2012) reported 76% reduction with PLA on iron ore, both slightly lower than the reduction achieved by BDS at 2%. The concentration-dependent performance of BDS—with the 2% concentration significantly outperforming the 1% concentration—reflects the greater density and continuity of the polymer network at higher concentrations, a phenomenon also observed by Ayseldeen et al. (2018) and Lemboye et al. (2021).

A pivotal finding of our study was the lack of significant improvement in the mean weight diameter (MWD) of aggregates for any of the treatments or the control. These results contrast with studies conducted on natural soils by Feizi et al. (2019) and Pouramin et al. (2025), in which soil modifiers such as bentonite and polymers significantly increased the stability of soil aggregates. Therefore, it can be inferred that the fundamental difference in substrate plays an important role in producing these results. In our study, a fine-grained concentrate with very low porosity was used, whereas soil studies have mainly focused on natural soils, particularly sandy soils. It therefore appears that the mulches were unable to penetrate deeply enough to create aggregates throughout the soil profile; instead, they formed a superficial, cohesive shell, thereby protecting the pile by resisting wind forces. Consequently,

they exhibited higher threshold velocities and lower erosion rates than the control. However, they did not affect the internal agglomeration measured by the MWD dry sieving method. This is advantageous because a reduced mulch content directly translates to a lesser effect on the inherent quality of the concentrate.

Furthermore, the cone penetration test (CPT) results revealed that molasses provided the highest surface resistance; however, this high resistance did not translate into improved wind erosion performance. This was because deep cracks developed during drying. These cracks exposed the concentrate particles to the wind and acted as focal points for wind erosion. Therefore, the higher erosion rate for molasses can be attributed to these cracks. In contrast, the BDS treatment, despite exhibiting lower CPT values, created a more continuous layer with fine, shallow cracks, consequently protecting the pile from wind erosion more effectively. These results indicate that for wind erosion control, the integrity and continuity of the protective layer are more critical than the absolute hardness of the surface.

Temporal Decline in Mulch Effectiveness

A key practical finding of this study is the observed decline in effectiveness over time. This reduction in performance can be attributed to degradation processes affecting the mulches. For biopolymers, and specifically for BDS, biopolymer chains undergo degradation due to microbial activity and UV radiation, reducing their binding capacity (Sharma et al., 2024; Dandin et al., 2025). Molasses, as a sugar-rich material, is also highly susceptible to rapid microbial consumption and chemical degradation (Nikseresht et al., 2020). The lime crust is vulnerable to external stresses such as wind and weathering due to its brittleness (Komaei et al., 2023). Therefore, any applied mulch must be periodically renewed.

Implications for Pellet Quality and Industrial Application

A significant advantage of BDS is its inert nature, which results in no negative impact on

the quality of the final product. The results showed that concentrates treated with BDS at 2% provided the required quality parameters, with drop number and cold compression strength (GCS) values falling within acceptable limits and comparable to pellets made with molasses (Table 6). These favorable product characteristics, combined with practical advantages that molasses lacks—such as being odorless, easier to store and handle, non-corrosive, and free from health and environmental problems—make BDS a more sustainable and reliable alternative to molasses for the steel industry. The results of this study are consistent with studies conducted on other cellulosic products for pellets, including Li et al. (2023), Sarkar and Hashemipour (2022), and Sivrikaya and Arol (2014).

Conclusion:

The main objective of this study was to compare the effectiveness of a novel cellulose-based biopolymer mulch (BDS) with conventional industrial mulches (lime slurry and sugarcane molasses) for controlling wind erosion from iron concentrate stockpiles in arid regions. Based on the results of this study, BDS at a concentration of 2% was the most effective mulch, achieving the lowest erosion rate (0.34 kg/m²/h) and the highest threshold wind velocity (54 km/h). In comparison, lime slurry (10%) and molasses (20%) achieved erosion rates of 1.8 and 1.1 kg/m²/h, with threshold velocities of 39.6 and 47.5 km/h, respectively. The effectiveness of all mulches declined over the three-week study period, with performance losses ranging from 40% (lime) to 50% (BDS at 2%), indicating the necessity of periodic reapplication.

A key mechanistic finding was that erosion control in industrial stockpiles relies primarily on surface crust integrity rather than on bulk aggregate stability. Despite significant differences in erosion rates among treatments, no statistically significant improvements were observed in mean weight diameter (MWD), indicating that mulches formed only a surface

protective layer rather than stabilizing the entire aggregate structure. This finding challenges the applicability of conventional soil stability indices to industrial materials and suggests that surface characterization methods should complement erosion rate measurements in performance evaluation.

The practical implications of this study extend to industrial operations and environmental regulation. BDS at 2% was the only treatment that met Iranian EPA standards for fugitive dust emissions (≤ 2.5 kg/m²/month) when applied at 14–21 day intervals. Additionally, pelletization tests confirmed that BDS at 2% does not adversely affect downstream processing, with drop number (2) and green compressive strength (3.5 kg/pellet) remaining within acceptable industrial limits. These findings, combined with the advantages of BDS over conventional mulches—including environmental compatibility, odorlessness, non-corrosiveness, and ease of storage and handling—position it as a viable alternative for sustainable dust management in the steel industry.

It should be noted that these conclusions are derived from a laboratory-scale study conducted over a three-week period. For industrial application of this material, its long-term durability and cost-effectiveness should be evaluated under real-world field conditions, where factors such as variable weather and large-scale application come into play, and a monitoring and reapplication schedule should be established. In general, investigating the effectiveness of BDS and similar environmentally friendly mulches can represent a significant step toward sustainable dust management, not only for iron concentrate but also for other fine-grained mineral and industrial materials, and offers promising solutions to reduce the challenge of wind erosion in industrial environments.

References:

1. Ahmad, S., Tariq, H., Abbas, S., Arshad, M., Mumtaz, A. & Ahmed, I. 2022. Organic

and synthetic mulching: Effects on soil-plant productivity and environment. *Mulching in agroecosystems: Plants, soil & environment*. Springer.

2. Ayeldeen, M., Negm, A., El Sawwaf, M. & Gädda, T. 2018. Laboratory study of using biopolymer to reduce wind erosion. *International Journal of Geotechnical Engineering*, 12, 228-240.

3. Badr, T. & Harion, J.-L. 2007. Effect of aggregate storage piles configuration on dust emissions. *Atmospheric Environment*, 41, 360-368.

4. Bethlehem, M. 2015. Review on soil stabilization using bagasse ash with lime and molasses with cement. Addis Ababa Science and Technology University, Addis Ababa.

5. Bhattacharya, P., Maity, P. P., Ray, M. & Mridha, N. 2021. Prediction of mean weight diameter of soil using machine learning approaches. *Agronomy Journal*, 113, 1303-1316.

6. Borowski, G. Using of adhesives and binders for waste agglomeration. 18th international symposium on waste management and sustainable landfilling, 2021. 11-15.

7. Dandin, S., Sathe, S., Ingle, G. & Rathod, R. 2025. Influence of biopolymers on geotechnical properties and erosion resistance of colliery spoil dumps. *Environmental Science and Pollution Research*, 32, 12455-12472.

8. Dos Reis Lemos Fontana, A., Da Silva, A. J. C., Pontes, L. S., Mesquita, A. L. A., Martins, M. F. & Dos Santos Junior, R. M. 2025. Wind tunnel study of iron ore dust emissions from stockpile and train wagons. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 47, 283.

9. Ekhtesasi, M. & Zare Chahouki, A. 2016. Wind erosion values of IRIFER Model and wind erosion meter comparison (Case study: Segzi plain in Esfahan province). *Iranian Journal of Range and Desert Research*, 23, 264-255.

10. Emami, H., Karimi, A. & Mina, M. 2021. Evaluation the efficiency of different

mulches to combat wind erosion of sandy soil running title: Efficiency of different mulches to control wind erosion. *Sustainable Earth Trends*, 1, 20-26.

11. Erci, V., Seker, C., Basaran, M. & Erpul, G. 2021. Determining the effectiveness of some soil stabilizers in wind erosion prevention using wind tunnel experiments. *Land Degradation & Development*, 32, 2962-2977.

12. Feizi, Z., Ayoubi, S., Mosaddeghi, M. R., Besalatpour, A. A., Zeraatpisheh, M. & Rodrigo-Comino, J. 2019. A wind tunnel experiment to investigate the effect of polyvinyl acetate, biochar, and bentonite on wind erosion control. *Archives of Agronomy and Soil Science*, 65, 1049-1062.

13. Feizi, Z., Sepahvand, S., Ranjbar, A. & Sekari, A. 2025. Effect of nanocellulose content in a polymer-based soil stabilizer on the wind erosion resistance of sandy soil under laboratory conditions. *Scientific Reports* 15, 42112.

14. Gao, W., Whalley, W. R., Tian, Z., Liu, J. & Ren, T. 2016. A simple model to predict soil penetrometer resistance as a function of density, drying and depth in the field. *Soil and Tillage Research*, 155, 190-198.

15. Geremew Kassa, M., Asemu, A. M., Belachew, M. T., Satheesh, N., Abera, B. D. & Alemu Teferi, D. 2024. Review on the application, health usage, and negative effects of molasses. *CyTA-Journal of Food*, 22, 2321984.

16. Hadjiev, A. & Hadjiev, P. 2003. On some methods for surface erosion control on tailings ponds and waste fly-ash piles. *Mining and mineral processing. Sofia* (46), 185-187.

17. Hassanvand, M. S., Torkian, A., Sahebnasagh, M. R., Naddafi, K. & Moayyedi, M. K. 2012. Experimental Investigation of the Effectiveness of Various Additives in Reducing Wind Erosion from Iron Ore Piles *Iranian Journal of Health and Environment*, 5, 387-398.

18. He, J.-J., Cai, Q.-G. & Tang, Z.-J. 2008. Wind tunnel experimental study on the effect of

PAM on soil wind erosion control. Environmental monitoring and assessment, 145, 185-193.

19. Hu, Y., Shi, L., Shan, Z., Dai, R. & Chen, H. 2020. Efficient removal of atmospheric dust by a suppressant made of potato starch, polyacrylic acid and gelatin. Environmental Chemistry Letters, 18, 1701-1711.

20. Komaei, A., Soroush, A., Fattahi, S. M. & Ghanbari, H. 2023. Influence of environmental stresses on the durability of slag-based alkali-activated cement crusts for wind erosion control. Science of The Total Environment, 902, 166576.

21. Kumar, M. A., Moghal, A. a. B., Rasheed, R. M. & Rehman, A. U. 2025. Enhancing durability and erosion resistance of soils with varying plasticity using crosslinked biopolymers. Scientific Reports, 15, 12572.

22. Kumar, S., Yadav, B. D. & Raj, R. 2024. A review on the application of biopolymers (xanthan, agar and guar) for sustainable improvement of soil. Discover Applied Sciences, 6, 393.

23. Lemboye, K., Almajed, A., Alnuaim, A., Arab, M. & Alshibli, K. 2021. Improving sand wind erosion resistance using renewable agriculturally derived biopolymers. Aeolian research, 49, 100663.

24. Li, X., Zhang, Y., Wang, Z., & Liu, H. 2023. A novel polymer-type binder to decrease bentonite dosage during iron ore pelletizing: Performance and mechanisms. Journal of Materials Research and Technology. 25, 1234–1246.

25. Ling, J., Yang, H., Tian, G., Cheng, J., Wang, X. & Yu, X. 2024. Direct reduction of iron to facilitate net zero emissions in the steel industry: A review of research progress at different scales. Journal of Cleaner Production, 441, 140933.

26. Liu, J., Wang, T., Jin, L., Li, G., Wang, S., Wei, Y., Ou, S., Wang, Y., Xu, J. & Lin, M. 2022. Suppression characteristics and mechanism of molasses solution on coal dust: A low-cost and environment-friendly

suppression method in coal mines. International Journal of Environmental Research and Public Health, 19, 16472.

27. Markiewicz, A., Koda, E., Kiraga, M., Wrzesiński, G., Kozanka, K., Naliwajko, M. & Vaverková, M. D. 2024. Polymeric products in erosion control applications: a review. Polymers, 16, 2490.

28. Nikseresht, F., Landi, A., Sayyad, G., Ghezlbash, G. & Schulin, R. 2020. Sugarcane molasse and vinasse added as microbial growth substrates increase calcium carbonate content, surface stability and resistance against wind erosion of desert soils. Journal of environmental management, 268, 110639.

29. Olbrich, H. 2006. The molasses. Biotechnologie-Kempe GmbH, 128.

30. Pandey, S. & Kumari, N. 2024. Utilisation of agricultural waste biopolymer for soil erosion management. Role of Green Chemistry in Ecosystem Restoration to Achieve Environmental Sustainability, 249-260.

31. Pouramin, M., Payan, M., Salimi, M., Ashournia, M., Zanganeh Ranjbar, P. & Saedi, A. 2025. Rapid Stabilization of Highly Expansive Clays: Synergistic Approach with Polyurethane and Waste Tire Textile Fiber for Enhanced Mechanical Properties. Journal of Materials in Civil Engineering, 37, 04025397.

32. Purohit, S., Pownceby, M. I. & Guiraud, A. 2025. Sticking and Swelling of Iron Ore Pellets: Mechanisms and Controlling Factors. Journal of Sustainable Metallurgy, 11, 67-87.

33. Rostami, N., Rabbani, M., Esmailbeigi, S., Hassanpour, K., Shahmoradi, M. H., Najafishoa, M., Ghobadian, Z., Varshosaz, M. & Norianfar, M. 2025. Development and construction of a portable wind tunnel for investigating wind erosion through the application of photogrammetry techniques. Scientific Reports, 15, 178.

34. Sagar, R. K., Kumar, R., Ks, S., Biswal, S. S., Umadevi, T., Sah, R. & Panda, D. K. 2025. Impact of Blaine No. on the Properties of

Iron Ore Pellets. *Mining, Metallurgy & Exploration*, 1-14.

35. Sarkar, S., & Hashemipour, M. 2022. Effect of binders on reduction degree and swelling behavior of iron ore pellets. *Ceramics International*, 48(11), 16345–16354.

36. Sharma, M., Tellili, N., Kacem, I. & Rouissi, T. 2024. Microbial biopolymers: from production to environmental applications—a review. *Applied Sciences*, 14, 5081.

37. Shojaei, S., Ardakani, M. a. H., Sodaiezhadeh, H., Jafari, M. & Afzali, S. F. 2021. New laboratory techniques (novel) in making organic-mineral mulch to control wind and water erosion and its use in global scale. *Spatial Information Research*, 29, 97-107.

38. Sivrikaya, O., & Arol, A. I. (2014). Alternative binders to bentonite for iron ore pelletizing: Part II – Effects on metallurgical and chemical properties. *HOLOS*, 30(1), 10–18.

39. Soldo, A., Miletić, M. & Auad, M. L. 2020. Biopolymers as a sustainable solution for the enhancement of soil mechanical properties. *Scientific Reports*, 10, 267.

40. Subudhi, R., Das, P., Kumar, A., Raju, J. T., Gautam, V. K., Yadav, N. K. & Dar, M. U. D. 2025. Role of Mulching in Reducing Erosion. *Erosion Measurement, Modeling, and Management*. Apple Academic Press.

41. Sujatha, E. R. 2024. Sustainable Solutions to Combat Soil Erosion Using

Biogenic Agents. *Global Sustainability: Trends, Challenges & Case Studies*, 37-60.

42. Susanto, A., Putro, E. K., Kusnadi, S. N. F., Rosalinawati, D., Santoso, M. D. & Manuel, A. A. 2024. Risk Assessment of Respirable Dust Exposure to Workers in the Mineral Ore Processing Industry. *The Indonesian Journal of Occupational Safety and Health*, 13, 109-115.

43. Taghizadeh, F., Mokhtarani, B. & Rahmanian, N. 2023. Air pollution in Iran: The current status and potential solutions. *Environmental Monitoring and Assessment*, 195, 737.

44. Tavares, J. H. R., Da Luz, J. a. M. & Ribeiro, F. F. 2025. Weathering impacts on iron ore pellets. *Caderno Pedagógico*, 22, e16669-e16669.

45. Vildan, E. 2024. Use of Polymers in Soil Erosion Control. *Current Studies in Materials Science and Engineering*.

46. Wang, J., Hu, X., Zhao, Y., Li, X., Zhao, P. & Guo, Y. 2024. Effects of molasses-based microbial dust suppressant on soil dust and microbial community. *Powder Technology*, 441, 119831.

47. Wang, L., Yao, Y., Li, J., Liu, K. & Wu, F. 2023. A State-of-the-Art Review of Organic Polymer Modifiers for Slope Eco-Engineering. *Polymers*, 15, 2878.

48. Žitnik, M. & Topić, N. 2012. Fugitive Dust Emissions from a Coal-, Iron Ore- and Hydrated Alumina Stockpile. In: KHARE, M. (ed.) *Air Pollution - Monitoring, Modelling and Health*. London: IntechOpen.