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Effectiveness of Protein and Polysaccharide Biopolymers as Dust Suppressants on Mine Soils: Results from Wind Tunnel and Penetrometer Testing

Johannes L. Sieger *, Bernd G. Lottermoser and Justus Freer

Institute of Mineral Resources Engineering, RWTH Aachen University, 52062 Aachen, Germany
* Correspondence: sieger@mre.rwth-aachen.de

Abstract: For the dust control of barren mine soils, protein and polysaccharide biopolymers have recently shown potential as environmentally friendly alternatives to conventional dust suppressants (e.g., salt brines or petroleum-based products). However, laboratory studies that determine suitable application parameters are required for large-scale field trials. This study performed wind tunnel and pocket penetrometer tests to investigate the wind erosion and penetration resistance of treatments with different biopolymer types, concentrations (wt%), and application rates (L/m^2) on two mine soils. The results demonstrate that all treatments significantly enhanced the wind erosion resistance of both tested soil types, with the biopolymer type, concentration, and application rate having a significant effect. Depending on the biopolymer type and application parameter, the wind-induced soil loss ranged from 0.86 to 423.9 g/m^2 (Control = 2645.0 g/m^2) for medium-grained sand and from 0.3 to 225 g/m^2 (Control = 26,177.0 g/m^2) for fine-grained silica sand, with the soil loss reducing as concentrations increase, until it reached a plateau concentration. For a similar performance, the tested proteins (wheat and fava bean protein) must be applied at higher concentrations than those of the polysaccharides (xanthan gum, corn starch, and carboxymethylcellulose). Spearman rank correlation revealed a moderate-to-strong negative correlation between soil loss (g/m^2) and penetration resistance (N), rendering the pocket penetrometer a rapid, low-cost, and indirect method for evaluating potential dust suppressants. This research contributes to evaluating biopolymers as alternatives to traditional dust suppressants for controlling dust emissions on barren surfaces. Biopolymers are biodegradable and can be sourced regionally at a relatively low cost, reducing the environmental impact and expenses associated with dust suppression.

Keywords: dust suppressant; dust control; biopolymer; wind tunnel; penetration resistance; mine soil; protein; polysaccharide

Citation: Sieger, J.L.; Lottermoser, B.G.; Freer, J. Effectiveness of Protein and Polysaccharide Biopolymers as Dust Suppressants on Mine Soils: Results from Wind Tunnel and Penetrometer Testing. *Appl. Sci.* **2023**, *13*, 4158. https://doi.org/10.3390/app13074158

Academic Editor: Daniel Dias

Received: 10 March 2023
Revised: 22 March 2023
Accepted: 22 March 2023
Published: 24 March 2023

1. Introduction

Mining operations cover extensive barren surfaces, such as tailings storage facilities, working benches, and dump sites. These are highly susceptible to wind erosion and lead to fugitive dust emissions, harming the environment, workforce, and surrounding communities [1–5]. Thus, those who own mine sites are challenged to act and implement effective dust control strategies. While the revegetation of such areas is not an operationally feasible option during the mine's production phase, the application of dust suppressants constitutes a proven mitigation method. However, while traditional commercial suppressants such as chloride salts, petroleum-based products, or polymers are effective, they are often costly, can have adverse environmental effects [6,7], may not be degradable, and their toxicity and potential health effects are largely unknown [8]. Thus, there is a need for environmentally benign, cost-effective, readily available, and easy-to-use alternatives.

Research on environmentally benign dust control and anti-desertification measures has gained increased attention in recent years and has mainly focused on biopolymers [9–13], food processing by-products and wastes [14–17], and enzyme or microbial-induced carbonate precipitates (EICP and MICP) [18–20]. Although EICP and MICP have shown high effectiveness and durability, their cultivation, application, and rejuvenation are difficult [21] and may require professional staff. While food processing by-products and wastes have demonstrated potential in several studies [14–17], their inconsistent composition and dry matter content limit their application potential. On the other hand, biopolymers have displayed potential as dust suppressants (e.g., [10,12,20,22–24]) and can constitute an environmentally benign, bio-based, biodegradable, and easy to use alternative to established dust suppressants. However, previous research primarily focused on polysaccharide biopolymers native to tropical and arid climates (e.g., guar, Persian, acacia, and locust bean gum, or pectin) [10,12,22], while research on polysaccharides and especially proteins that can be cultivated in continental climate remains underrepresented [9]. Furthermore, there is a lack of studies that aim to identify cost-effective application parameters suitable for first field tests, which are needed for bridging the gap between laboratory experiments and large-scale field testing.

In a recent study conducted by Sieger et al. [9], the dust suppressant potential of 14 polysaccharides and proteins from diverse botanical (corn, pea, wheat, cellulose, potato, and fava bean) and animal (pig, chicken, and cow) sources was demonstrated by laboratory tests, establishing the moisture retention, penetration resistance, and crust thickness of biopolymer-treated soil samples. While these methods are established screening techniques [10,23,25], they only offer an indirect indication of a substance's potential as a dust suppressant. For direct measurements of the wind erosion resistance of a biopolymer-treated soil, laboratory wind tunnel tests constitute an established method [10,26] and enable comparisons of the effectiveness of different biopolymer types, application rates (L/m^2), and concentrations (wt%). Thus, wind tunnel studies are required to further evaluate the dust suppression potential of selected polysaccharides and proteins and determine suitable field application parameters.

This study investigated the wind erosion and penetration resistance of soil samples treated with different biopolymer types, concentrations (wt%) and application rates (L/m^2) by performing laboratory wind tunnel and penetrometer tests on two different mine soils. In the first experimental phase, the effect of the biopolymer concentration on the samples' wind erosion resistance and crust strength was investigated. This allowed us to determine each biopolymer's plateau concentration, beyond which only marginal improvements in wind erosion resistance occur. In the second experimental phase, biopolymers were applied at the previously determined plateau concentration, and the effect of the application rate on the samples' wind erosion and penetration resistance was established. The results of this study contribute to the evaluation of polysaccharide and protein biopolymers as environmentally friendly dust suppressants and pave the way for large-scale field trials.

2. Materials and Methods

2.1. Soils

Two mine soils, which were already used by a previous study by Sieger et al. [9], were employed by this study: (a) medium-grained sand (D_{50} = 0.63 mm, C_u = 2.73), classified according to the unified soil classification system (USCS) as poorly-graded sand (SP) mainly consisting of quartz and plagioclase, and (b) fine-grained silica sand (D_{50} = 0.22 mm; C_u = 1.78), classified as medium-to-fine-grained, poorly-graded sand (SP) mainly consisting of quartz. A more detailed characterisation of the two soils can be found in Sieger et al. [9].

2.2. Biopolymers

In a previous study, Sieger et al. [9] investigated the potential of 14 polysaccharide and protein biopolymers as dust suppressants. Five biopolymers that showed strong potential in this previous study were selected for the present study (three polysaccharides and two proteins):

Xanthan gum (XG). Technical grade, readily dispersible XG was obtained from Jungbunzlauer Austria AG (AT). It is a white, free-flowing powder with a moisture content of 5.1 wt%. Due to its unique rheological properties, this microbial polysaccharide is primarily used in the oil drilling and food industry (e.g., for salad dressings, milk products, and sweets) [27]. In addition, XG is a widely studied biopolymer in soil stabilisation (e.g., [28–30]).

Corn starch (CS). Pre-gelatinised CS was obtained from Cargill B.V (NL). The polysaccharide comes as a white powder, has a moisture content of 5.8 wt%, and is primarily used as an instant thickener in the food industry (e.g., puddings, sauces, and bakery mixes).

Carboxymethylcellulose (CMC). Technical grade, low-viscosity CMC was obtained from Mikro-Technik-CMC (DE), comes as light-yellowish granules, and has a moisture content of 8.6 wt%. The polysaccharide is a cellulose derivative applied in the food, paper, textile, and other industries due to its diverse properties, such as mechanical strength and viscosity [31].

Fava bean protein concentrate (FBPC). Enzyme-activated FBPC was obtained from Aljoa-Starkelsen (LV), comes as a creamy, light-yellow powder, and has a moisture content of 8.8 wt%. The protein is obtained by milling fava beans and is primarily applied as a replacement for meat or wheat flour in the food industry [32].

Wheat protein (WP). Degraded wheat protein without viscoelastic properties was obtained from Kröner Stärke GmbH (DE), comes as a yellowish powder, and has a moisture content of 6.0 wt%. It is primarily used as a meat replacement and for sports nutrition.

2.3. Laboratory Experiments

Laboratory experiments comprised two consecutive test phases, whose sample programs are listed in Table 1 (Phase 1) and Table 2 (Phase 2). All experiments were performed on the previously mentioned two mine soils (medium-grained sand and fine-grained silica sand), with three replicates each (n = 3), including an untreated control (C). Both phases comprised wind tunnel (cf. Section 2.3.2) and pocket penetrometer testing (cf. Section 2.3.3). Phase 1 investigated the effect of the biopolymer concentration on wind-induced soil loss and crust penetration resistance, testing seven different biopolymer concentrations at a fixed application rate of 0.5 L/m^2 (Table 1). Based on Phase 1's wind tunnel tests, the 'plateau concentration' was determined for each tested biopolymer–soil combination. In this study, the plateau concentration denotes the concentration, beyond which only a marginal reduction of the wind-induced soil loss occurs. These 'plateau concentrations' were subsequently used for Phase 2, which investigated the effect of the application rate on wind-induced soil loss and crust penetration resistance, testing five different application rates (Table 2).

Table 1. Sample program of Phase 1, which investigated the effect of the biopolymer concentration on wind erosion resistance and crust penetration resistance.

Biopolymer/ Control	**Concentration (wt%)**											**Application Rate (L/m^2)**
	Medium-Grained Sand and Fine-Grained Silica Sand											
C	0.00											0.0
XG [a]		0.05	0.13	0.25	0.38		0.63	0.75				0.5
CS			0.13	0.25		0.50		0.75	1.00	1.25	1.50	0.5
CMC			0.13	0.25		0.50		0.75	1.00	1.25	1.50	0.5
FBPC			0.13	0.25		0.50		0.75	1.00	1.25	1.50	0.5
WP			0.13	0.25		0.50		0.75	1.00	1.25	1.50	0.5

Note. [a] = XG was tested at concentrations $\leq$ 0.75 wt%, but at finer intervals, as higher concentrations yielded too viscous solutions to be sprayable.

Table 2. Sample program of Phase 2, which tested the effect of the application rate on wind erosion and crust penetration resistance. The biopolymer concentrations were selected based on the results of Phase 1.

Biopolymer/ Control	Concentration (wt%)		Application Rate (L/m^2)			
	Medium-Grained Sand	Fine-Grained Silica Sand				
XG	0.05	0.13	0.2	0.3	0.4	0.6
CS	0.13	0.25	0.2	0.3	0.4	0.6
CMC	0.50	0.50	0.2	0.3	0.4	0.6
FBPC	0.75	1.00	0.2	0.3	0.4	0.6
WP	0.50	1.25	0.2	0.3	0.4	0.6

Note. The application rate of 0.5 L/m^2 was not tested again, as it was already included in Phase 1.

2.3.1. Sample Preparation

Three hundred and thirty-three samples were prepared for this study (Phase 1: 216 and Phase 2: 120). Air-dried soil was placed in stainless-steel trays (GN 1/3-trays) with dimensions of 176 × 325 × 40 mm and a sample surface area of 0.043 m^2 (Figure 1a). Samples were gently shaken to ensure slight and uniform compaction and levelled using a ruler. Biopolymer solutions were prepared by dissolving the biopolymers at the required concentration in distilled water for 10 min at room temperature using a magnetic stirrer (Figure 1b). The biopolymer's respective moisture content (see Section 2.2) was considered for calculating the required biopolymer mass. A trigger sprayer was used to spray the biopolymer solutions onto the samples. Accurate and uniform application was ensured by placing the samples on a precision scale (KERN PES 4200-2M, 0.001 g resolution) and spraying the biopolymer solution until the required dose was achieved (Figure 1c). Similar to Sieger et al. [9], a 3D-printed splash guard prevented the biopolymer solutions from inadvertently touching the weighing plate of the scale and distorting the scale readings.

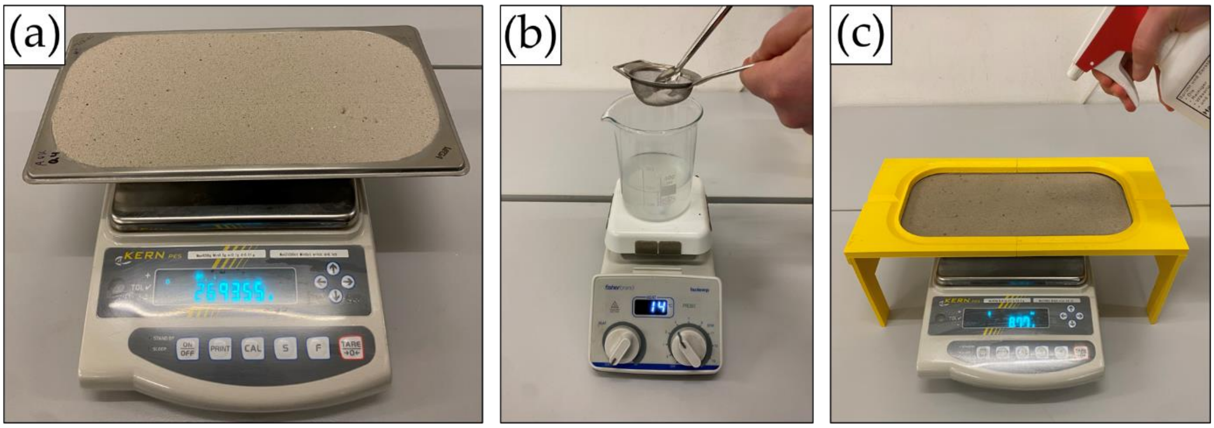

Figure 1. Sample preparation. (**a**) Weighing of dry sample, (**b**) preparation of biopolymer solution, and (**c**) gravimetric spray-on application with splash guard.

2.3.2. Wind Tunnel Tests

Wind tunnel tests were performed at the Institute of Mineral Resources Engineering (RWTH Aachen University, GER) with the wind tunnel set-up used by Freer et al. [15,16] (Figure 2). After their preparation (day 0), the samples were subjected to five wind tunnel cycles (days 2, 7, 14, 21, and 28). The samples were stored at an ambient temperature (21 ± 1 °C) and humidity (45 ± 2.5%) throughout this period. For each wind tunnel cycle, the samples were carefully placed in the test section and exposed for 120 s to a laminar airflow of 13.6 m/s (Figure 2f). Samples were weighed before and after each wind tunnel cycle using a precision scale (KERN PES 4200-2M) to calculate the gravimetric soil loss.

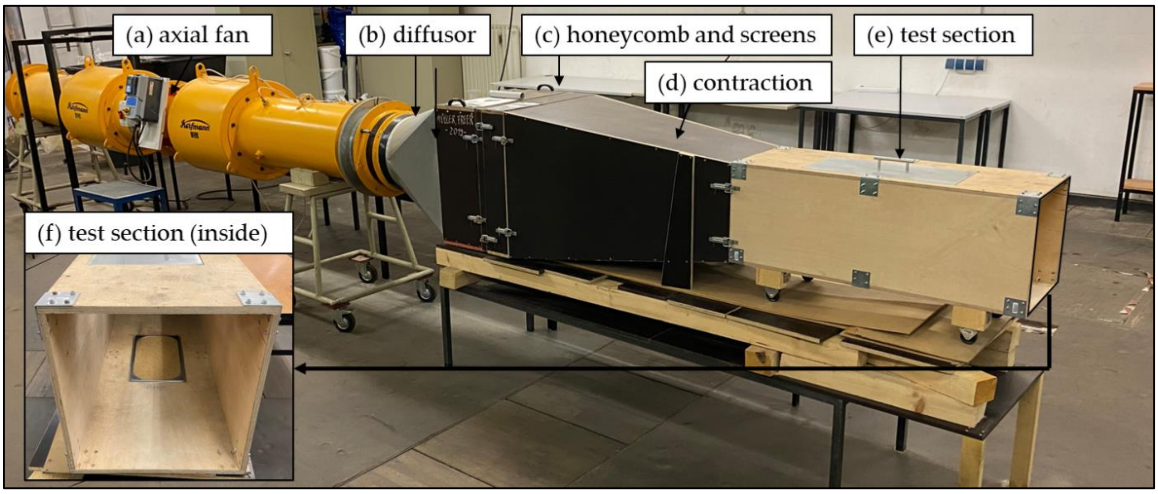

Figure 2. Wind tunnel and wind tunnel test section, showing individual components (**a**–**f**). Adapted from Freer et al. [15,16].

After the last wind tunnel cycle, each sample's cumulative soil loss (g) was determined and normalised to the total soil loss (g/m^2) by dividing it by the sample surface area. In addition, the dust control effectiveness relative to the control group (C) was established for each biopolymer treatment according to Equation (1):

$$Dust\ control\ effectiveness\ (\%) = 1 - \frac{\Delta m_{BP}}{\Delta m_C} \tag{1}$$

where Δm_{BP} denotes the total soil loss of the biopolymer-treated sample (g/m^2), and Δm_C denotes the total soil loss (g/m^2) of C. This allows the comparison of results with previous studies investigating the dust control effectiveness of treated soils (e.g., [20,33–35]).

2.3.3. Penetrometer Tests

After performing the last wind tunnel cycle, the penetration resistance (the crust strength) of the samples' crusts was measured using a hand-held dial-type pocket penetrometer (H 4205) (Figure 3a,b). The penetrometer has a 6.4 mm diameter flat-ended cylindrical tip, a load scale from 0 to 108 N (0.5 N resolution), and a lower reading limit of 0.5 N. Each sample was penetrated twice (at the top and bottom) at an angle of 90° by gradually increasing the load until the crust ruptured.

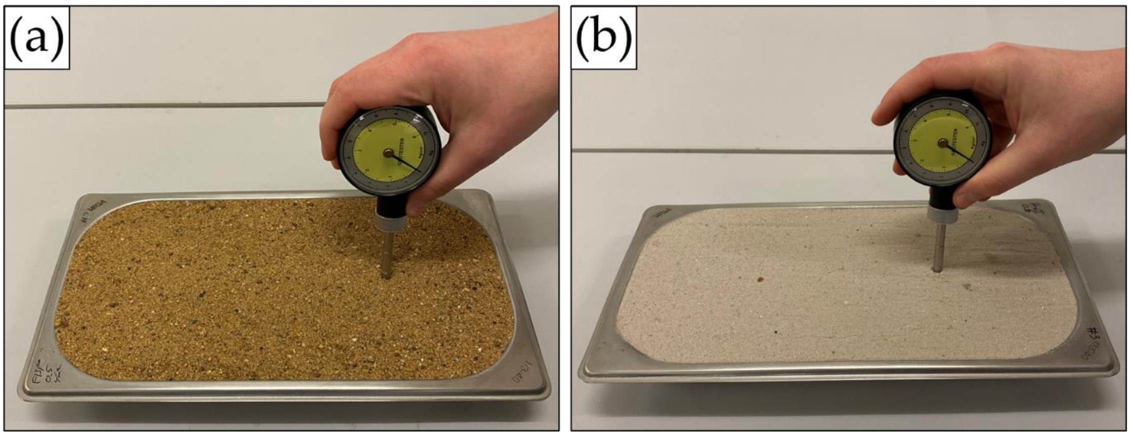

Figure 3. Hand-held pocket penetrometer testing. (**a**) Medium-grained sand sample; (**b**) fine-grained silica sand sample.

2.3.4. Statistical Analysis

Two-way analysis of variance (ANOVA) was performed with $\alpha = 0.05$. This statistical method is suitable for analysing whether two independent variables (i.e., biopolymer type, application rate (L/m^2), or concentration (wt%)) or their interaction have a statistically significant effect on a specified dependent variable (i.e., soil loss (g/m^2) and penetration resistance (N)). If the resulting *p*-value is <0.05, the corresponding independent variable has a significant effect on the dependent variable. In addition, the Spearman rank correlation coefficient was established to investigate the relationship between the samples' soil loss (g/m^2) and penetration resistance (N).

3. Results

3.1. Wind Tunnel Tests

3.1.1. Phase 1: Effect of Biopolymer Concentration on Wind-Induced Soil Erosion

Medium-grained sand. Figure 4 shows the wind-induced soil losses of medium-grained sand samples treated with different biopolymer types and concentrations (numerical values are appended in Table A1, Appendix A). All the biopolymer treatments significantly reduced the wind-induced soil loss compared to that of the control (C). The soil loss decreased at increasing concentrations until reaching a 'plateau concentration', beyond which only a marginal reduction of soil loss occurred. At lower concentrations, the polysaccharides (XG, CS, and CMC) tended to perform better than the tested proteins did (FBPC and WP). Treatments with XG and CS resulted in very low soil losses at the lowest tested concentrations (XG = 0.05 wt% and CS = 0.13 wt%), with higher concentrations leading only to marginal improvements. Conversely, treatments with FBPC, WP, and CMC displayed higher soil losses at 0.13 wt%, which gradually reduced as the concentration increased. The WP- and CMC-treated samples showed no improvement in soil losses at 0.50 wt%, while FBPC plateaued at 0.75 wt%.

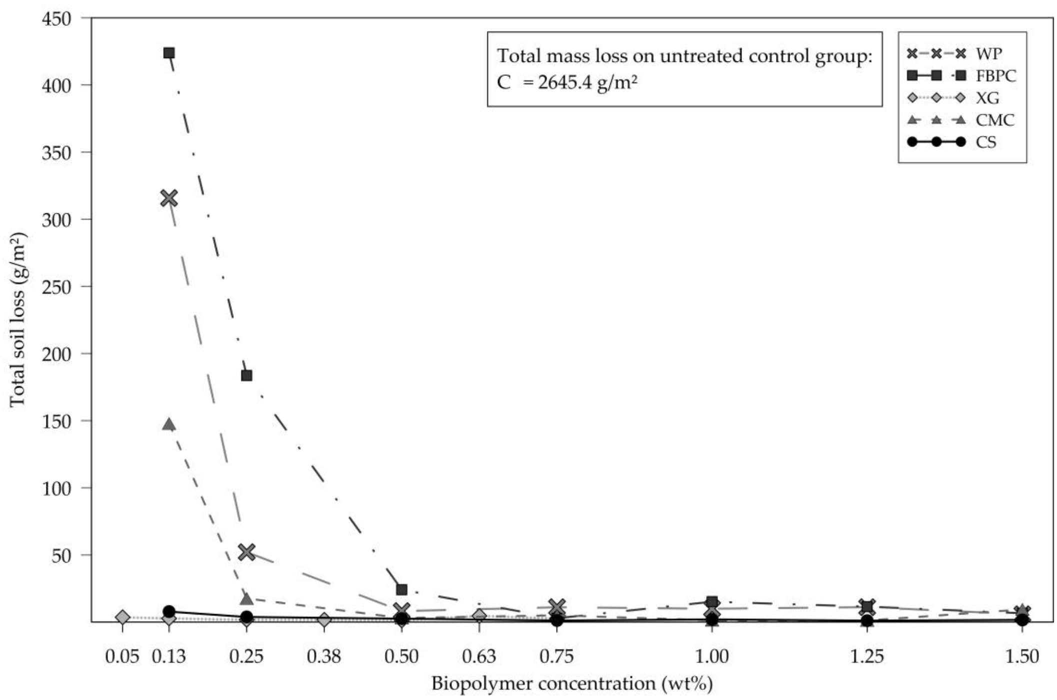

Figure 4. Total soil loss (g/m^2) of medium-grained sand samples treated with different biopolymer concentrations. Tests were performed in triplicate (n = 3). Note, numerical data (mean (M) and standard deviation (SD)) are appended in Table A1. Error bars representing the SD have been deliberately omitted for better legibility.

Fine-grained silica sand. The wind-induced soil losses of biopolymer-treated fine-grained silica sand samples are shown in Figure 5 (numerical values are appended in Table A1). Compared to the control, which experienced substantial soil loss, all the biopolymer treatments significantly reduced the wind-induced soil losses. As observed for medium-grained sand, the soil loss decreases as the biopolymer concentration increases, until it reaches a 'plateau concentration'. Again, the protein amendments (especially FBPC) showed noticeably higher soil losses at lower concentrations than the polysaccharide-treated samples did. Samples treated with XG displayed low soil loss at 0.05 wt%, reaching a stagnation concentration at 0.13 wt%. By contrast, the CS, CMC, and WP treatments showed moderately higher soil losses at 0.13 wt%, which decreased at higher concentrations. While CS stagnated at 0.25 wt%, CMC stagnated at 0.50 wt% and WP stagnated at 1.25 wt%, respectively. Lastly, amendments with 0.13 wt% FBPC displayed the highest soil loss, but these values reduced significantly as the concentration increased until they plateaued at 1.0 wt%.

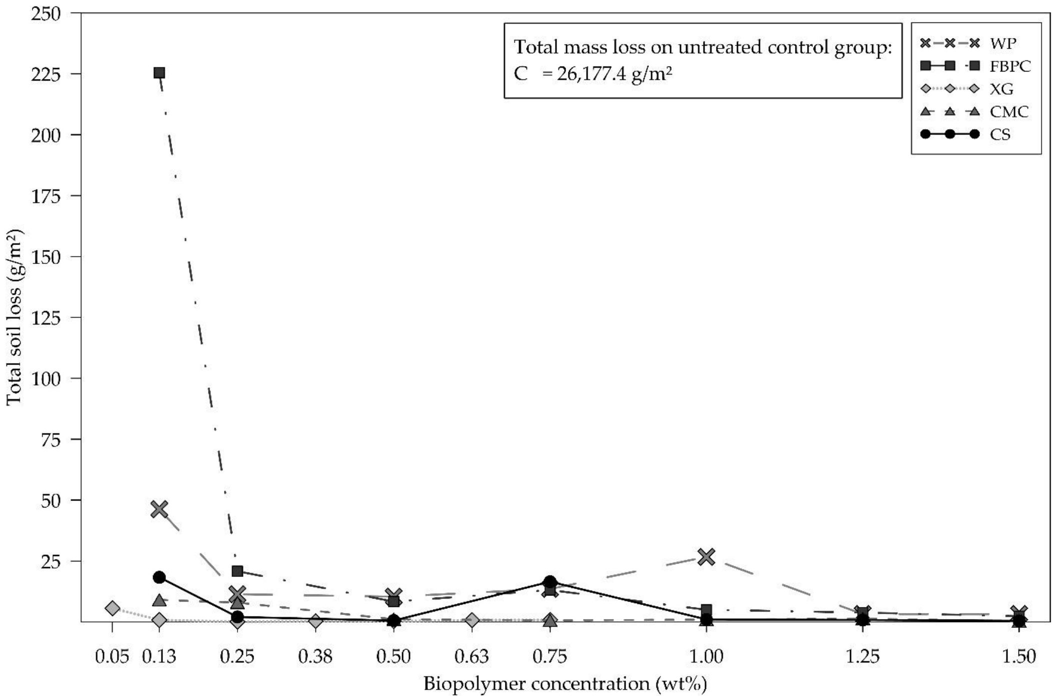

Figure 5. Total soil loss (g/m^2) of fine-grained silica sand samples treated with different biopolymer concentrations after the fifth wind tunnel cycle. Tests were performed in triplicate (n = 3). Note, numerical data (mean (M) and standard deviation (SD)) are appended in Table A1. Error bars representing the SD have been deliberately omitted for better legibility.

3.1.2. Phase 2: Effect of Biopolymer Application Rate on Wind-Induced Soil Erosion

Medium-grained sand. Figure 6 displays the results of the wind tunnel tests conducted with samples treated at different application rates and the biopolymers' respective plateau concentrations (see Table 2). The corresponding dust control effectiveness values are appended in Table A3. While the control group demonstrated considerable soil loss, all the biopolymer-treated samples, regardless of biopolymer type and application rate, displayed only marginal soil losses and achieved dust control effectiveness >99%. Upon closer examination of the biopolymer treatments, it is evident that some biopolymers performed slightly better than the others did. Applications with CMC, XG, and FBPC behaved similarly, exhibiting no clear trend, as their soil loss only slightly varied as the application rate increased. By contrast, the soil loss exhibited by samples treated with WP and CS slightly increased at higher application rates.

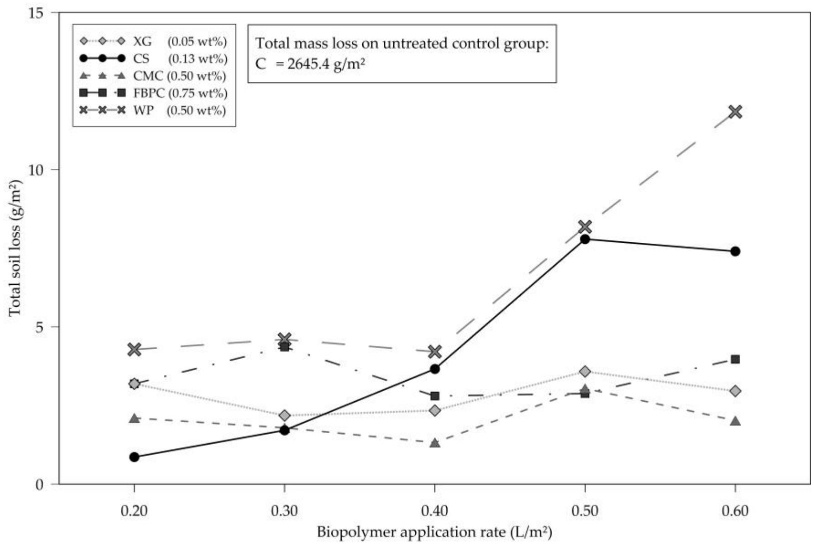

Figure 6. Total soil loss (g/m^2) of medium-grained sand treated at their plateau concentration at different biopolymer application rates. Tests were performed in triplicate (n = 3). Note, numerical data (mean (M) and standard deviation (SD)) are appended in Table A2. Error bars representing the SD have been deliberately omitted for better legibility.

Fine-grained silica sand. The results of the wind tunnel tests performed with fine-grained silica sand samples treated at different application rates and their respective plateau concentrations (Table 2) are shown in Figure 7. Compared to the control group, which exhibited substantial soil loss, all the biopolymer treatments significantly enhanced the wind erosion resistance, irrespective of the biopolymer type and application rate, achieving dust control effectiveness >99% (Table A3). The total soil losses of samples treated with CS, WP, and CMC were relatively stable as the application rate increased, while the XG-treated samples showed slightly stronger fluctuations in terms of soil loss. By contrast, treatments with FBPC benefitted noticeably from increasing the application rate to 0.3 L/m^2, beyond which only minor changes occurred.

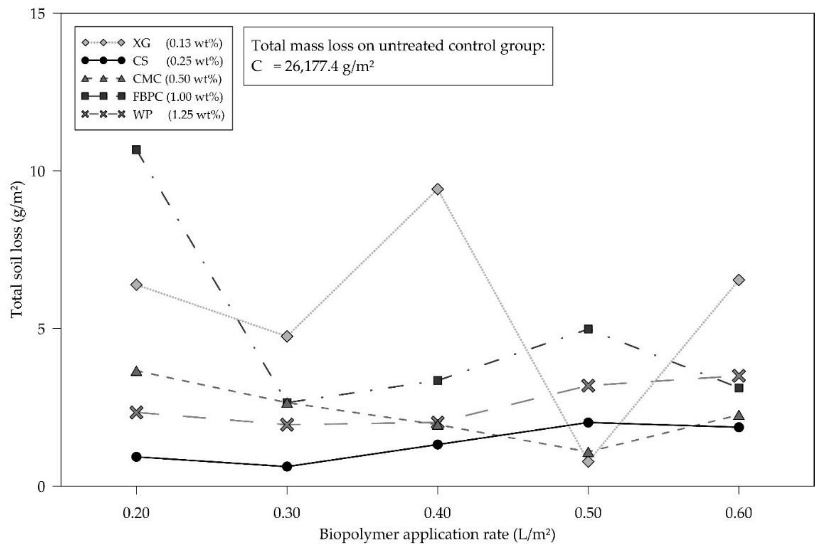

Figure 7. Total soil loss (g/m^2) of fine-grained silica sand samples treated at their plateau concentration at different biopolymer application rates after the fifth wind tunnel cycle. Tests were performed in triplicate (n = 3). Note, numerical data (mean (M) and standard deviation (SD)) are appended in Table A2. Error bars representing the SD have been deliberately omitted for better legibility.

3.2. Penetrometer Tests

3.2.1. Phase 1: Effect of Biopolymer Concentration on Crust Penetration Resistance

Medium-grained sand. The results of the pocket penetrometer tests on medium-grained sand after the fifth wind tunnel cycle are presented in Figure 8 (see Table A4 for numerical values). The control group showed no penetration resistance (lower reading limit of pocket penetrometer = 0.5 N). By contrast, all the biopolymer treatments formed crusts, with the penetration resistance tending to increase as the concentration increased. While most biopolymer types achieved similar penetration resistances at lower concentrations, the differences became more distinct at higher concentrations. CS formed the strongest crusts at concentrations >0.75 wt%, followed by CMC and FBPC, while the XG-treated samples had comparably strong crusts at concentrations <0.38 wt%. In addition, the penetration resistance of XG-, WP-, CMC-, and CS-treated samples peaked at concentrations of 0.38, 1.0, 1.25, and 1.25 wt%, respectively, and stagnated or slightly dropped beyond these concentrations.

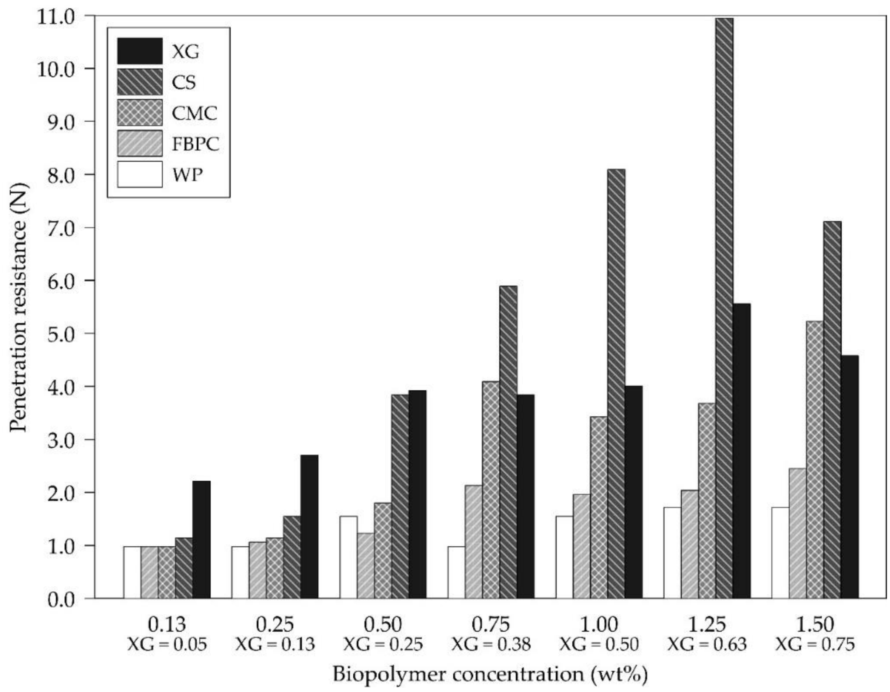

Figure 8. Penetration resistance of crusts after last wind tunnel test on day 28 on medium-grained sand. Penetration resistance tests were performed with six replicates (n = 6) with two penetrations per sample. The numerical data (mean (M) and standard deviation (SD)) are appended in Table A4.

Fine-grained silica sand. Figure 9 shows the results of pocket penetrometer tests performed on fine-grained silica sand after the fifth wind tunnel cycle. Similar to the medium-grained sand, the control group exhibited no measurable penetration resistance, while all the biopolymer treatments formed crusts, with the penetration resistance tending to increase at higher concentrations. The polysaccharide treatments (XG, CMC, and CS) generally displayed higher penetration resistances than the protein treatments did (WP and FBPC). XG formed relatively strong crusts at the lower tested concentrations and is only surpassed by CMC and CS at concentrations $\geq$0.75 wt% (XG $\geq$ 0.38 wt%). The penetration resistance of WP- and FBPC-treated samples plateaued at concentrations of 0.50 and 0.75 wt%, respectively. In contrast, XG- and CMC-treated samples peaked at 0.63 and 1.50 wt%, respectively, after stagnating at lower concentrations.

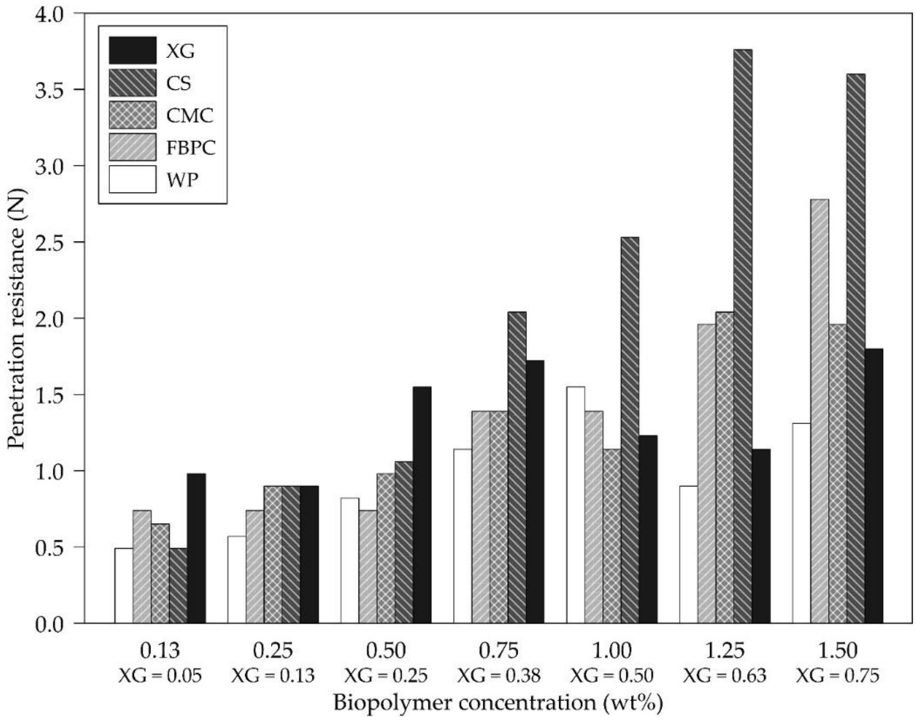

Figure 9. Penetration resistance of crusts after last wind tunnel test on day 28 of fine-grained silica sand. Penetration resistance tests were performed with six replicates (n = 6) with two penetrations per sample. Numerical data (mean (M) and standard deviation (SD)) are appended in Table A4.

3.2.2. Phase 2: Effect of Biopolymer Application Rate on Crust Penetration Resistance

Medium-grained sand. The penetrometer test results of biopolymer-treated medium-grained sand samples prepared at different application rates and the biopolymers' respective plateau concentrations are shown in Figure 10. The control group showed no measurable penetration resistance, while all the biopolymer treatments formed crusts. Although the absolute crust strengths of the samples were relatively weak, the penetration resistances generally increased at higher application rates. Despite differing plateau concentrations, most of the treatments achieved relatively similar penetration resistances at the individual application rates. Notably, treatments with FBPC, XG, and CMC formed the strongest crusts and displayed a clear trend of increasing penetration resistances at higher application rates. Contrarily, the WP and CS treatments did not exhibit a clear trend, with the crust strength of CS-treated samples peaking at 0.2 L/m^2 and that of WP-treated samples peaked at 0.5 L/m^2, respectively.

Fine-grained silica sand. Figure 11 displays the results of the penetrometer tests performed on fine-grained silica sand treated with different application rates at the biopolymers' respective plateau concentrations. All the biopolymer treatments exhibited relatively low penetration resistances, mostly ranging from 0.5 to 1.5 N, with the penetration resistance increasing slightly at higher application rates. Despite the differing plateau concentrations used for the different biopolymer types, most of the treatments resulted in similar penetration resistances at the respective application rates. The proteins (FBPC and WP) and CMC produced the strongest crusts, but they were also applied at higher concentrations than CS and XG were.

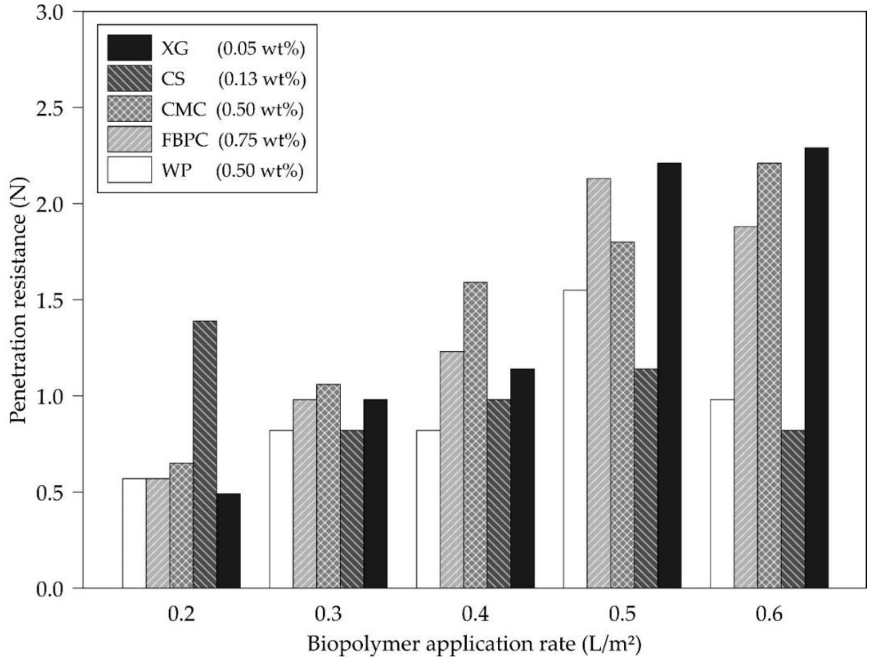

Figure 10. Penetration resistance of crusts from medium-grained sand samples, performed after the fifth wind tunnel cycle on day 28. Biopolymers were applied at their respective plateau concentration determined in Phase 1. Each of the three prepared samples was penetrated at the top and bottom of the centre (n = 6). The numerical results are appended in Table A5.

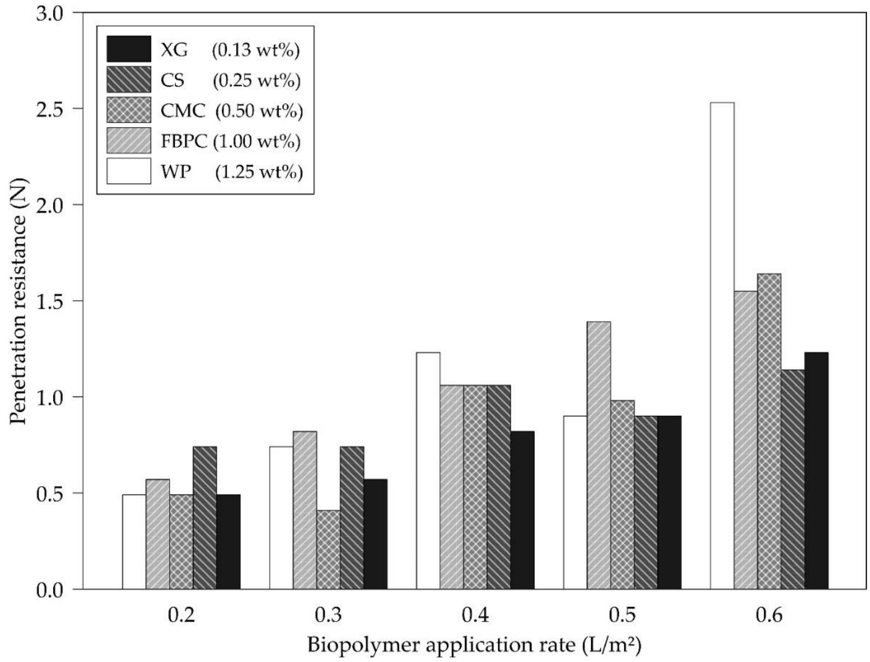

Figure 11. Penetration resistance of crusts from fine-grained silica sand samples performed after the fifth wind tunnel cycle on day 28. Biopolymers were applied at their respective plateau concentration determined in Phase 1. Each of the three prepared samples was penetrated at the top and bottom of the centre (n = 6). The numerical results are appended in Table A5.

3.3. Statistical Analysis

Wind tunnel tests: Phase 1. The results of the two-way ANOVA (Table 3) of the wind tunnel test data reveal that for both tested soil types, the biopolymer type ($p < 0.001$) and concentration ($p < 0.001$) have a significant effect on wind-induced soil loss. Some biopolymer types achieve higher wind erosion resistance than others do, and the soil loss generally decreases as the concentration increases until it reaches a plateau concentration.

Table 3. Results of two-way ANOVA ($\alpha = 0.05$) of wind tunnel test data from Phase 1, investigating the effect of the concentration on the wind-induced soil loss.

Factor	Medium-Grained Sand					Fine-Grained Silica Sand				
	SS	df	MS	F	p	SS	df	MS	F	p
Type	136,232.79	4	34,058.20	32.7	<0.001	21,479.42	4	5369.85	53.5	<0.001
Concentration	380,509.42	6	63,418.24	60.9	<0.001	40,628.28	6	6771.38	67.5	<0.001
Interaction	355,037.08	24	14,793.21	14.2	<0.001	86,459.69	24	3602.49	35.9	<0.001
Error	72,859.77	70	1040.85			7025.46	70	100.36		

Note. SS = sum of squares, df = degrees of freedom, MS = mean square, F = F-value, and p = p-value.

Wind tunnel tests: Phase 2. For medium-grained sand, the results of the two-way ANOVA show that the biopolymer type ($p < 0.001$) and application rate ($p < 0.001$) significantly affect wind erosion resistance (Table 4). Some biopolymer types perform slightly better than others do, and the soil loss increases slightly as the application rate increases. On fine-grained silica sand, only the biopolymer type ($p < 0.050$) appears to have a significant effect, unlike the application rate ($p = 0.568$), exhibiting no observable trend.

Table 4. Results of two-way ANOVA ($\alpha = 0.05$) of wind tunnel test data from Phase 2, investigating the effect of the application rate on the wind-induced soil loss.

Factor	Medium-Grained Sand					Fine-Grained Silica Sand				
	SS	df	MS	F	p	SS	df	MS	F	p
Type	106.33	4	26.58	10.7	<0.001	196.99	4	49.25	2.6	<0.050
Application rate	160.87	6	40.22	16.1	<0.001	55.96	6	13.99	0.7	0.568
Interaction	124.30	24	7.77	3.1	<0.050	217.03	24	13.56	0.7	0.761
Error	124.58	70	2.49			941.9	70	18.84		

Penetrometer tests: Phase 1. For both tested soil types, the results of the two-way ANOVA reveal that the biopolymer type ($p < 0.001$) and concentration ($p < 0.001$) have a significant effect on the samples' penetration resistance (Table 5). Some biopolymer types achieve higher penetration resistances than others do, and the penetration resistance generally increases with higher concentrations.

Table 5. Results of two-way ANOVA ($\alpha = 0.05$) of penetration resistance test data of Phase 1, investigating the effect of the concentration on the crust penetration resistance.

Factor	Medium-Grained Sand					Fine-Grained Silica Sand				
	SS	df	MS	F	p	SS	df	MS	F	p
Type	479.4	4	119.9	82.7	<0.001	26.4	4	6.61	20.2	<0.001
Concentration	332.3	6	55.38	38.2	<0.001	65.3	6	10.9	33.2	<0.001
Interaction	283.7	24	11.82	8.16	<0.001	37.8	24	1.57	4.8	<0.001
Error	253.5	70	1.45			57.4	70	0.33		

Penetrometer tests: Phase 2. For the penetrometer tests performed in Phase 2, the two-way ANOVA shows that the biopolymer type has a significant effect on the penetration resistance of both the medium-grained sand ($p < 0.001$) and the fine-grained silica sand ($p < 0.05$) (Table 6). Additionally, the application rate significantly affects penetration resistance ($p < 0.001$), with penetration resistance generally increasing at higher application rates.

Table 6. Results of two-way ANOVA (α = 0.05) of penetration resistance test data of Phase 2, investigating the effect of the application rate on the crust penetration resistance.

Factor	Medium-Grained Sand					Fine-Grained Silica Sand				
	SS	df	MS	F	p	SS	df	MS	F	p
Type	6.75	4	1.69	10.5	<0.001	2.66	4	0.67	5.0	<0.05
Application rate	23.62	6	5.9	36.8	<0.001	20.90	6	5.23	39.6	<0.001
Interaction	14.79	24	0.92	5.8	<0.001	7.16	24	0.45	3.4	<0.001
Error	20.07	70	0.16			16.50	70	0.13		

Correlation between soil loss and penetration resistance. The Spearman rank correlation was established to analyse the relationship between the total soil loss (g/m^2) and crust penetration resistance (N). In Phase 1, a strong negative correlation was observed for medium-grained sand ($r(106) = -0.81$, $p < 0.001$), and a moderate negative correlation was observed for fine-grained silica sand ($r(106) = -0.51$, $p < 0.001$), indicating that the soil loss tends to decrease as the penetration resistance increases. For the results of Phase 2, only weak negative correlations for medium-grained sand ($r(80) = -0.2$, $p = 0.123$) and fine-grained silica sand ($r(80) = -0.1$, $p = 0.296$) were found.

4. Discussion

4.1. Wind-Induced Soil Erosion

On sandy soil, biopolymers act by coating the sand particles and forming a cross-linked 3D network, which increases inter-particle cohesion [36]. Upon curing, these agglomerated particles become a surficial crust, which exhibits enhanced mechanical properties and can sustain erosive forces. Several wind tunnel studies have investigated the effect of biopolymers and other soil amendments on soil wind erosion resistance [10,12,13,16,22–24,26,37–40]. The key results of these studies have been compiled and appended in Table A6 and are recommended as references throughout the discussion. In the following, the key trends regarding the effect of the biopolymer type, concentration, application rate, and the resulting dust control effectiveness are discussed.

4.1.1. Effect of Biopolymer Type

The results showed that all tested biopolymer types significantly enhanced the samples' wind erosion resistance on both tested soil types (Figures 4 and 5). When they were applied at their respective plateau concentration, all the biopolymers exhibited dust control effectiveness >99%, with no distinct differences among the tested biopolymer types (Table A3). As can be seen in Table A6, these trends are consistent with most previous research, which also found that all the biopolymers tested significantly improved soil wind erosion resistance and achieved an effectiveness of >90% (with many of them having an effectiveness of >95%). However, some previous studies reported lower effectiveness rates than those in this study and revealed more distinct differences in soil loss among the various tested biopolymer types. These discrepancies can be attributed to differences in the experimental setups. For instance, Toufigh and Ghassemi [10], Chen et al. [38], and Ayeldeen et al. [26] performed wind tunnel tests at significantly higher velocities (20 m/s in [10], 17.6 m/s in [38], and 41.6 m/s in [26]) than this study (13.6 m/s), resulting in higher soil losses and more distinct differences among the tested biopolymer types. Furthermore, some studies employed more challenging testing conditions, such as placing the samples at angles of 25 or 30° into the test section [23,24,26] or incorporating saltation bombardment [13], which revealed more distinct differences among the biopolymer types.

While all the tested protein and polysaccharide treatments significantly enhanced the soil's wind erosion resistance, at the lower tested concentrations, the protein-treated samples (FBPC and WP) exhibited noticeably higher soil losses for both the tested soil types than those of the polysaccharides (XG, CS, and CMC) (Figures 4 and 5). As previous wind tunnel studies have not examined the wind erosion resistance of protein-treated soils, this observation can only be compared with a previous study investigating the crust strength of biopolymer-treated soil. Here, Sieger et al. [9] found that polysaccharide treatments tend to form stronger crusts than proteins do, which is also consistent with the results of the pocket penetrometer tests conducted by this study (Figures 8 and 9). Thus, it is believed that the tested polysaccharides have better inter-particle cohesion, and thus, crust-forming properties than the tested proteins do.

Aside from the differences between the biopolymer classes (proteins and polysaccharides), there were also noticeable differences in soil loss among the tested biopolymer types (CMC, CS, XG, FBPC, and WP), especially at the lower tested concentrations. This indicates that not only the biopolymer category (polysaccharide or protein), but also the biopolymer type, significantly affects the wind erosion resistance and is supported by the results of the two-way ANOVA (Table 3). This finding is consistent with the existing literature, which also found that some biopolymer types achieve higher dust control efficiencies than others do (Table A6). This study showed that XG performs better than CMC and CS do when they are applied at similar concentrations (Figures 4 and 5). However, Toufigh and Ghassemi [10] found that CMC treatments achieve lower soil losses than XG does, which could be due to the different XG types used in the two respective studies. While Toufigh and Ghassemi [10] applied XG at up to 1.5 wt% without reporting difficulties regarding the spray-ability, the viscosity of XG used in the present study limited the testing concentration to 0.75 wt%. Furthermore, in contrast to the findings of this study, a wind tunnel study by Ayeldeen et al. [26] indicated that corn starch performed better than XG did. As concluded before, this is also likely due to the different types and qualities of CS and XG used in the studies. This underlines that the quality and functional properties may significantly vary across different biopolymers of the same type.

4.1.2. Effect of Concentration

For both of the tested soil types, the experimental results showed that the wind-induced soil loss decreases significantly with an increasing biopolymer concentration until they reach a plateau concentration, beyond which only marginal changes occur (Figures 4 and 5). The two-way ANOVA also reveals that the concentration has a significant effect on wind-induced soil loss (Table 3). These trends are generally consistent with the existing literature (e.g., [12,13,23,24] and Table A6), which also reported that the soil loss decreases with an increasing biopolymer concentration until it reaches a plateau. Only one exception was reported by Dagliya et al. [22], who observed that the dust control effectiveness of an Acacia gum treatment decreased when the concentration was increased from 2.0 to 3.0 wt%. This decrease can likely be attributed to an increase in biopolymer viscosity that prevented proper coating of soil particles, leading to the formation of a crust with a lower wind erosion resistance.

It should be noted that the determined plateau concentrations only represent the experimental setup and methodology used in this study. Thus, they do not necessarily constitute the optimum concentration for field tests in which environmental factors such as biodegradation and precipitation play a decisive role. However, the determined plateau concentrations allow the comparison of the effectiveness of different biopolymer types with each other. While for medium-grained sand, XG (0.05 wt%) and CS (0.13 wt%) exhibited very low soil losses at low tested concentrations, CMC (0.50 wt%), FBPC (0.75 wt%), and WP (0.50 wt%) had to be applied at significantly higher concentrations to achieve similar performances. Thus, for future considerations, an application with XG and CS will likely be more efficient than the other biopolymers tested were.

4.1.3. Effect of Application Rate

The experimental results showed that irrespective of the application rate tested, all the biopolymer treatments considerably reduced wind-induced soil loss for both tested soil types (Figures 6 and 7). This suggests that at their respective plateau concentrations, all the biopolymers were able to effectively agglomerate particles on the sample surface to a crust, already at a low application rate of 0.2 L/m^2. Similar trends have also been reported by Owji et al. [13] and Kavazanjian et al. [40] (Table A6). Both studies found that increasing the application rate only slightly reduced the soil loss. However, similar to this study, the lowest application rates tested in their studies already resulted in marginal soil loss. Contrary to these studies, Lemboye et al. [12] showed that increasing the application rate to 0.5 wt% in Acacia gum treatments significantly reduced the soil loss, whereas equally weighted treatments with Sodium alginate and Pectin already displayed high wind erosion resistance at the lower application rate. Likewise, Freer et al. [16] also found that higher application rates significantly improved wind erosion resistance in a study that evaluated food processing by-products as dust suppressants. Thus, it can be concluded that increasing the application rate generally increases the soil's wind erosion resistance. However, this effect was not evident in this and previous studies [12,13,40], as low application rates already resulted in very low soil loss. It is believed that more challenging testing conditions, such as higher velocity, repeated wet-dry cycles, or testing inclined samples, would have revealed the effect of the application rate more distinctively.

For medium-grained sand, the results of Phase 2 showed that the soil loss slightly increased at application rates >0.4 L/m^2, with the two-way ANOVA indicating that the application rate has a significant effect ($p < 0.001$) (Table 4). This minor trend contradicts the existing literature and is likely related to soil surface disturbances caused by spraying the biopolymer solution onto the samples, resulting in some sand particles not sufficiently adhering to the soil matrix. By contrast, such a trend was not evident for the fine-grained silica sand samples ($p = 0.568$), likely because its finer and more uniform grain size distribution results in a more homogeneous surface less susceptible to wind erosion. Nevertheless, as this trend was only very marginal, it is not considered to be relevant for future potential field applications.

4.1.4. Evaluation of the Dust Control Effectiveness

On both tested soil types, the results demonstrated that applications at the biopolymers' respective plateau concentrations resulted in high dust control effectiveness >99%, even at a low application rate of 0.2 L/m^2 (Figures 6 and 7, and Table A3). For the given experimental setup and methodology, this implies that a low application rate was already sufficient to properly coat and agglomerate the surface particles to a wind erosion-resisting crust. However, careful interpretation is required when one is comparing these results with previous studies due to the different experimental setups and tested parameters.

Compared to most previous research, this study tested relatively low biopolymer dosages with concentrations between 0.05 and 1.5 wt% and application rates between 0.2 and 0.6 L/m^2, but also, less demanding wind tunnel conditions (horizontal sample placement and 13.6 m/s). Two studies performed wind tunnel tests with similar parameters [39,40]. Kavazanjian et al. [40] tested Xanthan gum (0.1 wt% and 0.4 L/m^2) and Chitosan (0.1 wt% and 0.5 L/m^2) on horizontally placed sand with silt (SM) samples at 7.2 m/s, and they also reported effectiveness >99% (Table A6). Similarly, Erci et al. [39] tested a commercial hydrogel ($\geq$4 wt% and 0.3 L/m^2) on sand with silt (SM) and silty clay loam (CH) samples at velocities of 9 and 11 m/s, and they also reported effectiveness >86%. It is thus concluded that the results of this study are consistent with previous studies testing similar parameters. In contrast to this study, previous studies often tested substantially higher concentrations (from 0.4 up to 10 wt%) and application rates (from 1 to 3.5 L/m^2), but they also subjected the samples to more challenging testing conditions, such as an angular sample placement and velocities ranging from 14.8 to 41.6 m/s [10,12,13,22–24]. Most of these studies also showed very high dust control effectiveness >90%.

Hence, the resulting dust control effectiveness reported by different studies cannot simply be compared with each other, and this also does not enable us to infer the potential performance of a dust suppressant in field conditions. However, dust control effectiveness is a valuable parameter for comparing the performances of a combination of application rate, concentration, and biopolymer type within an experimental study. Moreover, for the tested biopolymers, it enables the definition of application parameters at which the tested biopolymers will likely demonstrate similar performances.

4.2. Penetrometer Tests

Several studies performed penetrometer testing to investigate the penetration resistance of biopolymer-treated soils (e.g., [9–13,23,24]). These studies demonstrated that biopolymer type, concentration, and application rate have a significant effect on the crust's penetration resistance. In the following, the effect of the type, concentration, and application rate of biopolymers on the penetration resistance are discussed.

4.2.1. Effect of Biopolymer Type

On both tested soil types, all the biopolymer treatments formed crusts, with penetration resistances ranging between 0.5 and 10.95 N, while the control group exhibited no measurable penetration resistance (e.g., Figures 8 and 9). Thereby, the biopolymer type has a significant effect ($p < 0.001$) on the penetration resistance, with some biopolymers forming stronger crusts than others do (Tables 5 and 6). These trends are consistent with the existing literature, showing that biopolymer-treated soils form crusts with different strengths depending on the biopolymer type (e.g., [9,10,12,41]).

However, compared to results from the existing literature (Table A6), the penetration resistances measured in this study were mostly lower (Figures 8 and 9). For instance, for soil samples treated with Acacia Gum, Lemboye et al. [12] reported penetration resistances between 10 and 145 N, between 7.5 and 25 N for Sodium alginate, and between 15 and 39 N for Pectin, respectively. While these penetration resistances are significantly higher than the results of the present study, Lemboye et al. [12] tested higher application rates (1.3 and 3.5 L/m^2) and concentrations (0.5 and 5.0 wt%), which explains the resulting discrepancies. In addition, as this study tested penetration resistance after performing the fifth wind tunnel cycle, the repeated handling, weighing, and wind tunnel exposure inevitably impaired the integrity of the crust, which is a further reason explaining the relatively low penetration resistances.

For fine-grained silica sand, the test results showed that the protein treatments (WP and FBPC) did not achieve penetration resistances as high as those of the polysaccharides (XG, CMC, and CS), which were also applied to medium-grained sand samples treated with biopolymer concentrations <0.75 wt%. The WP treatments achieved the lowest penetration resistances on both the tested soil types (Figures 8 and 9). These trends are in agreement with a previous study by Sieger et al. [9], who also found that polysaccharide treatments tend to form stronger crusts than protein-treated samples do. In their study, WP treatments also produced relatively weak crusts. In addition, the results of this study show that at equal concentrations, treatments with XG form stronger crusts than CMC does. By contrast, Toufigh and Ghassemi [10] reported that CM treatments produce higher penetration resistances than XG does. However, Toufigh and Ghassemi [10] likely performed their tests with a less potent XG than that in the present study, as they tested XG applications up to 1.5 wt% concentration without reporting the difficulties regarding viscosity. By contrast, the XG used in this study already yields highly viscous solutions that cannot be sprayed at concentrations >0.75 wt%.

4.2.2. Effect of Concentration

For both the tested soil types, the penetrometer results showed that increasing the concentration significantly increased the penetration resistance of most of the tested biopolymers until it reached a plateau, beyond which the penetration resistance either stagnates or even slightly decreases (Figures 8 and 9, and Table 5). This trend is mostly consistent with findings from previous studies, which also observed that increasing the biopolymer concentration results in a higher crust strength (e.g., [12,23,24]).

The results of this study showed that the crust strength of some treatments (e.g., XG and WP) tended to stagnate or even slightly drop beyond a certain threshold concentration.

This observation differs from previous studies, which did not exhibit this trend as clearly. This discrepancy can likely be attributed to differences in test dosages and methods. While this study tested relatively low application rates and concentrations and conducted tests using a hand-held pocket penetrometer (calibrated spring), previous studies mainly tested higher application rates (from 1.3 to 3.5 L/m^2) and concentrations (from 0.3 to 10 wt%) and performed tests using precise laboratory penetrometers (loading machine mounted with penetrometer pin) [10–13,23,24]. Thus, a direct comparison of the penetration resistances measured in this study with previous studies is limited. Due to the low tested dosages, the crusts exhibited relatively low penetration resistances, with often indistinct differences, so that differences could not be detected using the pocket penetrometer. By contrast, the high dosages tested by previous studies resulted in significantly stronger crusts with more distinct differences in crust strength that are precisely measurable using the stationary laboratory penetrometer.

4.2.3. Effect of Application Rate

Penetrometer tests performed with samples prepared at different application rates showed that the penetration resistance of most biopolymer-induced crusts slightly increased at higher application rates (Figures 10 and 11). For both tested soil types, the two-way ANOVA also indicated that the application rate significantly affects penetration resistance (Table 6). This trend is consistent with previous studies examining the effect of the application rate on the penetration resistance of biopolymer-treated soils [12,13]. Thereby, the main difference is that previous studies revealed more distinct differences in penetration resistance than the present study did. However, this can be attributed to the generally low tested application rates and small intervals (i.e., 0.2, 0.3, 0.4, 0.5, and 0.6 L/m^2) relative to the rates tested by previous studies (i.e., 1 and 2 L/m^2 by [13]; 1.3 and 3.5 L/m^2 by [12]).

4.3. Correlation between Penetration Resistance and Wind Erosion Resistance

Wind tunnel testing is a valuable method for directly measuring the wind erosion resistance of soils and provides essential information for evaluating potential dust suppressants and application parameters. However, besides a (typically) stationary wind tunnel, this method requires a spacious laboratory, time, and a comparably high sample volume. Moreover, the comparison of experimental results among different studies is limited due to the unique setup of each wind tunnel and the variety of testing parameters, including velocity, exposure duration, wet–dry cycles, and sample placement, as highlighted in Section 4.1.4 and Table A6. Furthermore, as found in the present and previous studies (Table A6), many tested treatments achieve high levels of dust control effectiveness (>90%) at relatively low dosages, implying that the wind tunnel method may not reveal distinct differences in crust integrity for samples treated at higher dosages. In this context, complementary pocket penetrometer testing can provide further valuable insights.

The results of the Spearman rank correlation (for Phase 1) showed a moderate-to-strong negative correlation between soil loss (g/m^2) and penetration resistance (N) for fine-grained silica ($r(106) = -0.51$, $p < 0.001$) and medium-grained sand ($r(106) = -0.81$, $p < 0.001$). Similarly, Toufigh and Ghassemi [10] and Ding et al. [11] also reported a strong correlation between the wind erosion resistance and penetration resistance of biopolymer-treated samples. Hence, pocket penetrometer testing provides an indirect indicator for inferring the wind erosion resistance of stabilised soil. Moreover, pocket penetrometer testing is a rapid, portable, low-cost method that can be used to complement wind tunnel testing or, on its own, as a screening method to obtain preliminary insights prior to conducting more detailed wind tunnel experiments.

As a result of this correlation, and also previously concluded by Lemboye et al. [12], penetration resistance, thus, allows researchers to gaining deeper insights into differences among the different treatments. This is especially helpful to reveal differences in crust integrity among samples with a similarly high dust control effectiveness. In the context of this study, this implies that biopolymer treatments, which exhibited relatively high penetration resistances, will likely exhibit a higher wind erosion resistance than the treatments with a lower crust strength will. For medium-grained sand, this implies that treatments with CS, XG, and partially, FBPC likely exhibit a higher wind erosion resistance than the WP treatments do, whereas for fine-grained silica sand, CS, XG, and CMC will likely perform better.

The results of Phase 2 were not suitable for estimating a correlation coefficient, as they only displayed very low soil losses and penetration resistances with little variability. Due to the lack of data variability, the Spearman ranking correlation showed no correlation.

4.4. Evaluation of the Potential of the Tested Polysaccharides and Proteins as Dust Suppressants on Mine Sites

Wind tunnel testing and pocket penetrometry are established methods for evaluating potential dust suppressants [9,10,25,41]. The wind tunnel experiments performed in this study demonstrate that all the tested biopolymer treatments effectively agglomerate soil particles and form crusts with high wind erosion resistance, even at relatively low biopolymer concentrations and application rates. Complementary pocket penetrometer testing revealed weak penetration resistances, which in hindsight of the low tested dosages, are consistent with previous studies that tested biopolymers ([9–13,23,24]). Therefore, it can be concluded that all the tested biopolymer types show potential to be applied as dust suppressants, with polysaccharides proving to be more effective than proteins are at lower concentrations.

While the laboratory test results provided useful indications for suitable application parameters, true optimum application parameters can only be determined through iterative testing in field conditions. Thereby, effective application in field conditions will likely require higher dosages, as environmental factors such as rainfall [12], UV radiation [42], and temperature fluctuations [43] significantly influence the durability of the treatment. Since biopolymers are biodegradable and water-soluble, they will likely require more frequent rejuvenation intervals than commercially available petroleum-based products or synthesised polymers, which are typically less degradable and mobile and require less frequent application [8,44].

For potential large-scale applications, economic considerations are essential and must account for the costs of the biopolymer, water, equipment, fuel, personnel, and required rejuvenation intervals. The tested biopolymers are available at relatively low cost, with the indicative bulk prices being XG = USD 2.0–3.0/kg, CMC = USD ~1.4/kg, CS < USD 1.0/kg, FBPC = USD 1.4–2.5/kg, and WP = USD ~1.4–2.5/kg) [45–49], respectively. Thereby, polysaccharides (especially starches) are mostly cheaper than proteins are. Equipment, fuel, and personnel are required to dissolve the biopolymers with an agitator in water and spray it on the soil using conventional water trucks or field sprayers with booms. Thereby, as water scarcity is increasing in various countries (e.g., Chile [50]), the cost of water may become a decisive factor in future. As many mining operations worldwide still solely rely on spraying pure water for dust control on haul roads and exposed surfaces, introducing biopolymers may reduce water consumption.

Aside from cost-effectiveness-related considerations, the environmental friendliness, biodegradability, availability, and ease of use constitute further relevant parameters for evaluating the dust suppression potential of biopolymers. The biopolymers tested in this study are all biodegradable, and due to their frequent use in food and other industries, they have been very well studied and characterised [27,31,47]. By contrast, commercially available dust suppressants can have adverse environmental effects, partially have proprietary formulations, or have been studied insufficiently [6,7]. Except for microbial XG, the raw material of the tested biopolymers is regionally available from abundant biomass sources, such as cellulose (CMC), corn (CS), wheat (WP), or fava beans (FBPC). In addition, previous studies have also demonstrated that biopolymers can be extracted and used for soil stabilisation from wastes and by-products, such as casein (milk waste) [51,52], collagen (leather waste) [53,54], and CMC (paper waste) [55]. The tested biopolymers are easy to use, as they can be simply dissolved in water and sprayed onto the field with conventional spraying equipment, while other approaches, such as MICP, are more challenging to apply [21].

Consequently, the tested biopolymers show potential as an environmentally friendly, highly available, low-cost, and easy-to-apply alternative to established dust suppressants. Further large-scale field studies are required to examine their effectiveness in real field conditions and raise awareness in the mining industry.

5. Conclusions

This study performed laboratory wind tunnel and penetrometer tests to investigate the wind erosion and penetration resistance of biopolymer-treated soil samples treated with different biopolymer types, concentrations (wt%) and application rates (L/m^2) on two different mine soils. The following conclusions can be drawn based on the results.

1. In the first laboratory trial, the wind-induced soil losses of medium-grained sand ranged from 1.09 to 423.9 g/m^2 (C = 2645.4 g/m^2) and from 0.3 to 225.5 g/m^2 (C = 26,177.4 g/m^2) for fine-grained silica sand, showing that all the treatments significantly enhanced the wind erosion resistance relative to that of the control. Increasing the concentration reduced the soil loss until it reached a plateau concentration, and the protein treatments achieved similar wind erosion resistances as those of the polysaccharides, but they required higher concentrations.
2. In a second laboratory trial, biopolymers were applied at their respective plateau concentration and different application rates. For medium-grained sand, the soil loss ranged from 0.86 to 23.19 g/m^2 (C = 2645.4 g/m^2), and for fine-grained silica sand, it ranged from 0.62 to 10.67 g/m^2 (C = 26,177.4 g/m^2), showing that all the treatments achieved a very high dust control effectiveness regardless of the tested application rate. The reason for this is that application at the plateau concentration resulted in a high wind erosion resistance at all tested application rates.
3. The results of the pocket penetrometer tests ranged from 0.98 to 10.95 N (C < 0.5 N) for medium-grained sand and from 0.5 to 3.76 N (C < 0.5 N) for fine-grained silica sand. Thereby, the crust strength was significantly affected by the biopolymer type ($p < 0.001$) and increased significantly at higher concentrations ($p < 0.001$) and application rates ($p < 0.001$). In addition, the Spearman rank correlation revealed a moderate-to-strong negative correlation between soil loss (g/m^2) and penetration resistance (N) for fine-grained silica ($r(106) = -0.51$, $p < 0.001$) and medium-grained sand ($r(106) = -0.81$, $p < 0.001$). This implies that the pocket penetrometer can serve as an indirect indicator for evaluating the performance of potential dust suppressants.

This study demonstrated that the tested polysaccharides and proteins have the potential to be applied as dust suppressants and facilitated the selection of application parameters suitable for first field trials.

Author Contributions: Conceptualization, J.L.S. and J.F.; methodology, J.L.S. and J.F.; formal analysis, J.L.S.; investigation, J.L.S.; data curation, J.L.S.; writing—original draft preparation, J.L.S.; writing—review and editing, J.L.S., B.G.L. and J.F.; visualization, J.L.S.; project administration, J.L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data supporting the findings of this study will be made available from the corresponding author upon reasonable request.

Acknowledgments: We thank the Rheinische Baustoffwerke GmbH and the Quarzwerke Frechen AG for providing the mine soils used in this study. We thank Devrim Gürsel and Stephanie Lohmeier for assisting in characterising the soil samples and Johannes J. Emontsbotz for designing and printing the 3D-printed splash guard. Last, the authors would like to thank the anonymous reviewers for their helpful comments and suggestions, which improved the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Results of Phase 1 wind tunnel tests. Total wind-induced soil loss after the fifth wind tunnel cycle on medium-grained sand C (M = 2645.40 g/m^2, SD = 783.60) and fine-grained silica sand C (M = 26,177.49 g/m^2, *SD* = 844.57).

Biopolymer Concentration (wt%)	Biopolymer									
	CS		CMC		XG		FBPC		WS	
	Total Soil Loss (g/m^2)									
	M	SD	M	SD	M	SD	M	SD	M	SD
Medium-grained sand										
0.13 (XG = 0.05)	7.79	2.04	147.90	77.88	3.58	1.41	423.91	103.68	315.81	32.12
0.25 (XG = 0.13)	3.82	0.48	17.60	8.35	2.73	0.72	183.64	74.14	52.10	22.39
0.50 (XG = 0.25)	2.57	0.66	3.04	0.87	1.71	0.77	24.14	3.32	8.18	2.31
0.75 (XG = 0.38)	1.17	0.38	5.06	3.22	1.71	0.11	10.44	0.88	11.06	1.85
1.00 (XG = 0.50)	2.02	0.79	1.32	0.29	1.25	0.29	15.19	11.76	9.97	2.04
1.25 (XG = 0.63)	1.09	0.29	1.17	0.38	4.60	3.22	11.53	5.93	11.14	3.77
1.50 (XG = 0.75)	1.64	0.87	9.42	11.19	2.65	0.40	6.62	1.60	5.84	1.32
Fine-grained silica sand										
0.13 (XG = 0.05)	18.30	6.29	9.03	4.91	5.61	6.62	225.47	19.07	46.26	18.29
0.25 (XG = 0.13)	2.02	1.34	7.94	7.18	0.78	0.29	20.79	3.03	11.37	2.96
0.50 (XG = 0.25)	0.55	0.11	1.09	0.61	0.08	0.11	8.33	4.91	10.36	0.94
0.75 (XG = 0.38)	16.51	17.07	0.62	0.55	0.31	0.29	13.08	8.76	13.55	9.42
1.00 (XG = 0.50)	1.01	0.44	0.93	0.33	0.31	0.29	4.98	1.44	26.71	31.22
1.25 (XG = 0.63)	0.78	0.40	1.32	0.77	0.70	0.19	3.82	1.05	3.19	0.61
1.50 (XG = 0.75)	0.47	0.50	0.31	0.29	0.78	0.55	2.34	1.06	3.19	1.17

Table A2. Results of Phase 2 wind tunnel tests. Total wind-induced soil loss on medium-grained sand (Control; M = 2645.40 g/m^2, SD = 783.60) and fine-grained silica sand (Control; M = 26,177.49 g/m^2, SD = 844.57). Samples were treated at their respective 'plateau concentration' based on the results of Phase 1.

Application Rate (L/m^2)	Biopolymer									
	CS		CMC		XG		FBPC		WS	
	Total Soil Loss (g/m^2)									
	M	SD	M	SD	M	SD	M	SD	M	SD
Medium-grained sand										
0.2	0.86	23.19	2.10	0.50	3.19	2.06	3.19	0.77	4.28	1.95
0.3	1.71	0.55	1.79	0.58	2.18	0.11	4.36	0.48	4.60	0.58
0.4	3.66	1.88	1.32	0.29	2.34	0.66	2.80	0.19	4.21	0.19
0.5	7.79	2.04	3.04	0.87	3.58	1.41	2.88	0.58	8.18	2.31
0.6	7.40	3.42	2.02	0.40	2.96	0.29	3.97	0.87	11.84	11.49
Fine-grained silica sand										
0.2	0.93	0.69	3.66	0.77	6.39	6.23	10.67	10.80	2.34	0.19
0.3	0.62	0.40	2.65	0.48	4.75	3.28	2.65	1.30	1.95	0.77
0.4	1.32	0.72	1.95	0.61	9.42	11.01	3.35	1.23	2.02	1.41
0.5	2.02	1.34	1.09	0.61	0.78	0.29	4.98	1.44	3.19	0.61
0.6	1.87	0.50	2.26	0.29	6.54	3.62	3.12	0.29	3.50	0.38

Note. Plateau concentrations on medium-grained sand (CS = 0.13 wt%, CMC = 0.50 wt%, XG = 0.05 wt%, FBPC = 0.75 wt%, and WS = 0.50 wt%) and on fine-grained silica sand (CS = 0.25 wt%, CMC = 0.50 wt%, XG = 0.13 wt%, FBPC = 1.00 wt%, and WS = 1.25 wt%).

Table A3. Dust control effectiveness for different application rates on medium-grained sand and fine-grained silica sand in relation to the untreated control group.

Application Rate (L/m²)	Biopolymer									
	CS		CMC		XG		FBPC		WS	
	Dust Control Effectiveness (%)									
	M	SD	M	SD	M	SD	M	SD	M	SD
Medium-grained sand										
0.2	99.968	0.026	99.921	0.020	99.879	0.080	99.879	0.030	99.838	0.076
0.3	99.935	0.022	99.932	0.023	99.918	0.004	99.835	0.019	99.826	0.023
0.4	99.862	0.077	99.950	0.012	99.912	0.027	99.894	0.008	99.841	0.008
0.5	99.706	0.097	99.885	0.042	99.865	0.067	99.962	0.038	99.691	0.110
0.6	99.720	0.183	99.923	0.021	99.888	0.016	99.850	0.047	99.847	0.056
Fine-grained silica sand										
0.2	99.996	0.123	99.986	0.138	99.976	1.114	99.959	1.931	99.991	0.034
0.3	99.998	0.043	99.990	0.052	99.982	0.359	99.990	0.142	99.993	0.084
0.4	99.995	0.066	99.993	0.056	99.964	1.001	99.987	0.111	99.992	0.128
0.5	99.992	0.129	99.996	0.059	99.997	0.028	99.981	0.139	99.988	0.059
0.6	99.993	0.041	99.991	0.024	99.975	0.295	99.988	0.024	99.987	0.031

Note. Plateau concentrations on medium-grained sand (CS = 0.13 wt%, CMC = 0.50 wt%, XG = 0.05 wt%, FBPC = 0.75 wt%, and WS = 0.50 wt%) and on fine-grained silica sand (CS = 0.25 wt%, CMC = 0.50 wt%, XG = 0.13 wt%, FBPC = 1.00 wt%, and WS = 1.25 wt%).

Table A4. Results of Phase 1 penetrometer tests. Penetration resistance of medium-grained sand and fine-grained silica sand samples treated at different biopolymer concentrations. Tests were performed on day 28 after initial treatment (after the fifth and last wind tunnel cycles). Each of the three prepared samples was penetrated at the top and bottom of the centre (n = 6).

Biopolymer Concentration (wt%)	Biopolymer									
	CS		CMC		XG		FBPC		WS	
	Penetration Resistance (N)									
	M	SD	M	SD	M	SD	M	SD	M	SD
Medium-grained sand										
0.13 (XG = 0.05)	1.14	0.61	0.98	0.00	2.21	0.79	0.98	0.00	0.98	0.00
0.25 (XG = 0.13)	1.55	0.52	1.14	0.23	2.70	0.93	1.06	0.18	0.98	0.00
0.50 (XG = 0.25)	3.84	1.08	1.80	0.46	3.92	1.42	1.23	0.25	1.55	0.34
0.75 (XG = 0.38)	5.89	1.88	4.09	0.23	3.84	0.96	2.13	0.23	0.98	0.00
1.00 (XG = 0.50)	8.09	1.94	3.43	1.10	4.01	2.51	1.96	0.75	1.55	0.52
1.25 (XG = 0.63)	10.95	3.39	3.68	1.09	5.56	1.08	2.04	0.34	1.72	0.37
1.50 (XG = 0.75)	7.11	1.94	5.23	0.54	4.58	1.12	2.45	0.40	1.72	0.47
Fine-grained silica sand										
0.13 (XG = 0.05)	0.50	0.00	0.65	0.23	0.98	0.28	0.74	0.25	0.50	0.00
0.25 (XG = 0.13)	0.90	0.34	0.90	0.44	0.90	0.18	0.74	0.25	0.57	0.18
0.50 (XG = 0.25)	1.06	0.18	0.98	0.00	1.55	0.6	0.74	0.25	0.82	0.37
0.75 (XG = 0.38)	2.04	0.82	1.39	0.34	1.72	0.47	1.39	0.44	1.14	0.23
1.00 (XG = 0.50)	2.53	1.00	1.14	0.37	1.23	0.25	1.39	0.34	1.55	0.60
1.25 (XG = 0.63)	3.76	1.12	2.04	0.60	1.14	0.23	1.96	0.57	0.90	0.18
1.50 (XG = 0.75)	3.60	0.88	1.96	0.85	1.80	0.54	2.78	1.22	1.31	0.37

Table A5. Results of Phase 2 penetrometer tests. Penetration resistance of medium-grained sand and fine-grained silica sand samples treated at different application rates and their respective plateau concentrations. Tests were performed on day 28 after initial treatment (after the fifth and last wind tunnel cycles). Each of the three prepared samples was penetrated at the top and bottom of the centre (n = 6).

Application Rate (L/m^2)	Biopolymer									
	CS		CMC		XG		FBPC		WS	
	Penetration Resistance (N)									
	M	SD	M	SD	M	SD	M	SD	M	SD
Medium-grained sand										
0.2	1.39	0.60	0.65	0.23	0.49	0.01	0.57	0.18	0.57	0.18
0.3	0.82	0.23	1.06	0.34	0.98	0.00	0.98	0.00	0.82	0.23
0.4	0.98	0.00	1.59	0.33	1.14	0.23	1.23	0.37	0.82	0.23
0.5	1.14	0.61	1.80	0.46	2.21	0.79	2.13	0.23	1.55	0.34
0.6	0.82	0.23	2.21	0.55	2.29	0.67	1.88	0.34	0.98	0.00
Fine-grained silica sand										
0.2	0.74	0.25	0.49	0.00	0.49	0.00	0.57	0.18	0.49	0.00
0.3	0.74	0.25	0.41	0.18	0.57	0.18	0.82	0.23	0.74	0.25
0.4	1.06	0.44	1.06	0.18	0.82	0.23	1.06	0.18	1.23	0.37
0.5	0.90	0.34	0.98	0.00	0.90	0.18	1.39	0.34	0.90	0.18
0.6	1.14	0.23	1.64	0.67	1.23	0.25	1.55	0.44	2.53	0.96

Note. Plateau concentrations on medium-grained sand (CS = 0.13 wt%, CMC = 0.50 wt%, XG = 0.05 wt%, FBPC = 0.75 wt%, and WS = 0.50 wt%) and on fine-grained silica sand (CS = 0.25 wt%, CMC = 0.50 wt%, XG = 0.13 wt%, FBPC = 1.00 wt%, and WS = 1.25 wt%).

Table A6. Compilation of results from previous studies performing wind tunnel tests. The experimental methodologies and set-ups applied in the studies below (e.g., wind tunnel type, velocity, exposure time, or sample angle) partially differ. For studies that did not directly report dust control effectiveness, the effectiveness was calculated based on data from the original sources according to Equation (1) (cf. Section 2.3.2).

Substance	Soil	D_{50} (mm)	C_u	V (m/s)	AR (L/m^2)	Concentration (%)					Dust Control Effectiveness (%)					Note	Reference
						C_1	C_2	C_3	C_4	C_5	C_1	C_2	C_3	C_4	C_5		
Acacia gum	SP	0.15	2.1	16.2	1.3	0.5	1.0	2.0	3.0	5.0	45.87	88.57	95.71	97.14	99.14	a	[12]
	SP	0.15	2.1	16.2	3.5	0.5	1.0	2.0	3.0	5.0	99.93	N/A	N/A	N/A	99.96	a	[12]
Sodium alginate	SP	0.15	2.1	16.2	1.3	0.5	1.0	2.0	3.0		98.84	N/A	N/A	99.99		a	[12]
	SP	0.15	2.1	16.2	3.5	0.5	1.0	2.0			99.99	N/A	99.99			a	[12]
Pectin	SP	0.15	2.1	16.2	1.3	0.5	1.0	2.0	3.0	5.0	99.99	99.99	99.99	99.99	99.99	a	[12]
	SP	0.15	2.1	16.2	3.5	0.5	1.0	2.0	3.0		99.99	99.99	99.99	99.99		a	[12]
Sodium alginate	SP	0.21	1.8	10	N/A	1.0	2.0				99.99	99.99				a	[22]
	SP	0.21	1.8	20	N/A	1.0	2.0				99.97	99.36				a	[22]
	SP	0.21	1.8	30	N/A	1.0	2.0				99.50	99.94				a	[22]
Pectin	SP	0.21	1.8	10	N/A	1.0	2.0				99.99	99.99				a	[22]
	SP	0.21	1.8	20	N/A	1.0	2.0				99.72	99.92				a	[22]
	SP	0.21	1.8	30	N/A	1.0	2.0				99.66	99.89				a	[22]
Acacia gum	SP	0.21	1.8	10	N/A	1.0	2.0	3.0			99.99	99.99				a	[22]
	SP	0.21	1.8	20	N/A	1.0	2.0	3.0			99.17	99.81	80.00			a	[22]
	SP	0.21	1.8	30	N/A	1.0	2.0	3.0			99.16	99.85	84.00			a	[22]
Xanthan gum	SP	0.13	2.1	20	1.9	0.5	1.0	1.5			77.08	87.50	93.75			b	[10]
	MT	0.28	9.4	20	1.9	0.5	1.0	1.5			78.00	88.00	92.00			b	[10]
	SP	0.22	7.5	20	1.9	0.5	1.0	1.5			76.09	89.13	91.30			b	[10]
Guar gum	SP	0.13	2.1	20	1.9	0.5	1.0	1.5			79.17	89.58	97.92			b	[10]
	MT	0.28	9.4	20	1.9	0.5	1.0	1.5			79.00	90.00	98.00			b	[10]
	SP	0.22	7.5	20	1.9	0.5	1.0	1.5			78.26	91.30	97.83			b	[10]
Carboxymethyl cellulose	SP	0.13	2.1	20	1.9	0.5	1.0	1.5			85.42	93.75	99.58			b	[10]
	MT	0.28	9.4	20	1.9	0.5	1.0	1.5			86.80	93.40	99.80			b	[10]
	SP	0.22	7.5	20	1.9	0.5	1.0	1.5			84.78	95.65	99.57			b	[10]
Guar gum	MT	0.15	34.0	17.6	1.9	0.6	1.0	1.6			68.70	88.70	96.52			b	[38]
Xanthan gum	MT	0.15	34.0	17.6	1.9	0.6	1.0	1.6			68.70	80.87	91.30			b	[38]
PAM	SP [c]	N/A	<5	20	2.0	0.4	0.8	1.2	1.6		98.09	99.32	99.55	99.98		b	[24]
Xanthan gum	SP [c]	N/A	<5	20	2.0	0.4	0.8	1.2	1.6		88.36	97.06	99.55	99.98		b	[24]
Guar gum	SP [c]	N/A	<5	20	2.0	0.4	0.8	1.2	1.6		95.69	99.43	99.55	99.98		b	[24]
Na-lignosulfonate	SP [c]	N/A	<5	20	2.0	2.0	4.0	6.0	8.0	10.0	65.00	89.00	99.00	99.00	99.00	b	[23]
Ca-lignosulfonate	SP [c]	N/A	<5	20	2.0	2.0	4.0	6.0	8.0	10.0	62.00	83.00	91.00	99.00	99.00	b	[23]
Molasses	CH	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		57.95	63.08	68.68	84.41		a	[39]
	CH	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		54.09	58.02	59.81	63.22		a	[39]
	SM	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		57.67	61.84	67.69	81.87		a	[39]
	SM	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		53.27	53.76	57.34	56.98		a	[39]

Table A6. *Cont.*

Substance	Soil	D_{50} (mm)	C_u	V (m/s)	AR (L/m^2)	Concentration (%)					Dust Control Effectiveness (%)					Note	Reference
						C_1	C_2	C_3	C_4	C_5	C_1	C_2	C_3	C_4	C_5		
Cement	CH	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		71.70	89.49	96.35	98.46		a	[39]
	CH	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		66.97	82.04	88.24	91.07		a	[39]
	SM	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		64.39	89.72	96.71	95.92		a	[39]
	SM	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		67.10	80.21	85.22	87.77		a	[39]
Molasses + cement	CH	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		92.39	97.95	99.27	99.76		a	[39]
	CH	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		79.31	99.40	99.72	99.87		a	[39]
	SM	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		87.40	93.54	99.34	98.83		a	[39]
	SM	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		75.36	96.70	97.83	99.07		a	[39]
Hydrogel	CH	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		75.36	88.97	97.15	98.68		a	[39]
	CH	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		71.19	89.86	92.32	98.02		a	[39]
	SM	N/A	N/A	9	0.3	2.0	4.0	8.0	16.0		66.16	90.98	98.02	97.60		a	[39]
	SM	N/A	N/A	11	0.3	2.0	4.0	8.0	16.0		72.02	86.41	88.02	98.21		a	[39]
Xanthan gum	SM	N/A	N/A	7.2	0.4	0.1					99.92					a	[40]
	SM	N/A	N/A	7.2	1.0	0.1					99.94					a	[40]
	SM	N/A	N/A	7.2	1.1	0.2					99.94					a	[40]
	SM	N/A	N/A	7.2	2.0	0.2					99.94					a	[40]
	SM	N/A	N/A	7.2	2.2	0.1					99.96					a	[40]
	SM	N/A	N/A	7.2	3.1	0.2					99.96					a	[40]
Chitosan	SM	N/A	N/A	7.2	0.5	0.1					99.28					a	[40]
Chicory vinasses	SP	0.63	2.7	13.6	1.0	1.0	2.0	4.0	6.0	8.0	42.98	66.15	79.30	88.10	93.33	a	[16]
Corn steep liquor	SP	0.63	2.7	13.6	1.0	1.0	2.0	4.0	6.0	8.0	45.20	90.26	97.94	99.62	99.78	a	[16]
Decantation Syrup	SP	0.63	2.7	13.6	1.0	1.0	2.0	4.0	6.0	8.0	60.09	77.41	97.98	99.56	99.41	a	[16]
Palatinose molasses	SP	0.63	2.7	13.6	1.0	1.0	2.0	4.0	6.0	8.0	68.55	92.19	98.98	99.57	99.59	a	[16]
Carboxmetyhl cellulose	SP-SM	0.16	2.2	14.8	1.0	0.3	0.5	0.7			97.80	98.30	98.71			b	[13]
	SP-SM	0.16	2.2	14.8	2.0	0.3	0.5	0.7			98.10	98.94	99.02			b	[13]
Guar gum	SP-SM	0.16	2.2	14.8	1.0	0.3	0.5	0.7			90.70	92.70	93.50			b	[13]
	SP-SM	0.16	2.2	14.8	2.0	0.3	0.5	0.7			90.90	93.49	97.90			b	[13]
Xanthan gum	ML	0.03	30.0	41.6	d	0.3	0.5	0.8			44.72	57.76	75.16			b	[26]
Carrageenan gum	ML	0.03	30.0	41.6	d	0.3	0.5	0.8			39.76	45.97	60.87			b	[26]
Guar gum	ML	0.03	30.0	41.6	d	0.3	0.5	0.8			78.89	90.07	93.16			b	[26]
Modified starches	ML	0.03	30.0	41.6	d	0.3	0.5	0.8			67.71	79.50	88.21			b	[26]

Note. a = dust control effectiveness calculated based on the untreated control group, b = dust control effectiveness calculated based on the water-treated control group, c = red sand (bauxite residue), and d = biopolymer solution mixed-in into soil at 15 wt%, Abbreviations. AR = application rate, C_1–C_6 = concentrations tested in the respective study, CH = fat clay, ML = silt, MT = Mine tailings, N/A = not available, RS = red sand, SL = sandy loam, SM = sand with silt, SP = poorly graded sand, SP-SM = poorly graded sand with silt, and V = wind velocity.

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