Biopolymere als Staubbindemittel auf Brachflächen des Bergbaus: Ergebnisse aus Labor- und Feldversuchen

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Biopolymers as Dust Suppressants on Barren Mine Soils: Results from Laboratory Studies and Field Trials

Von der Fakultät für Georessourcen und Materialtechnik der
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German Abstract

Durch Wind verursachte Staubemissionen aus aktiven und stillgelegten Bergwerken stellen nicht nur eine Bedrohung für lokale Ökosysteme und die Gesundheit der Belegschaft dar, sondern beeinträchtigen auch angrenzende Gemeinden. Die Staubemissionen stammen meist von großen, exponierten, brachliegenden Flächen wie Abraumhalden, Bergedämmen, oder Arbeitssohlen und sind schwer kontrollierbar. Diese Problematik wird in Zukunft an Bedeutung gewinnen, da sowohl die Abbauflächen als auch die Häufigkeiten und Intensität von Dürreperioden und Starkwindereignissen weltweit zunehmen werden. Der Einsatz von Staubbindemitteln wie Wasser, Salzlösungen oder erdölbasierten und synthetischen Polymeren ist eine etablierte Methode zur Unterdrückung von Staubemissionen auf brachliegenden Flächen. Während die Wirkung von Wasser jedoch im Zuge der Verdunstung schwindet, sind herkömmliche Staubbindemittel vergleichsweise teuer, können negative Auswirkungen auf die Umwelt haben und sind nicht biobasiert. Da die Bergbauindustrie vor der Herausforderung steht, ihre Umweltbelastungen zu reduzieren und klimafreundlicher zu werden, bedarf es folglich umweltfreundlicher und biobasierter Staubbindemittel, die kostengünstig, verfügbar, und anwendungsfreundlich sind.

Das Potenzial von Biopolymeren zur Stabilisierung von Böden und Minderung von Staubemissionen wurde zuletzt vermehrt von Wissenschaftler untersucht. Biopolymere werden von Pflanzen, Tieren oder Mikroorganismen synthetisiert (z. B. Stärke, Zellulose, Gelatine, oder Xanthan). Das Potenzial einer Vielzahl von Polysacchariden und Proteinen aus Quellen, die in kontinentalen Klimazonen beheimatet sind, ist jedoch bislang nur unzureichend erforscht. Darüber hinaus wurde die Wirksamkeit von Biopolymeren zur Minderung windinduzierter Staubemissionen bislang nicht in großflächigen Feldversuchen untersucht. Die vorliegende Arbeit setzt an diesen Lücken an und zielt auf die Beantwortung der folgenden Hauptforschungsfrage ab: „*Welches Potenzial haben Polysaccharid- und Proteinbiopolymere als Staubbindemittel zur Unterdrückung von Staubemissionen auf Brachflächen des Bergbaus?*“. Zur Beantwortung dieser Frage wurde die Arbeit in drei aufeinander folgende Studienphasen unterteilt, deren Ergebnisse in drei entsprechenden Forschungsartikeln veröffentlicht wurden: Eine Laborscreeningstudie (Artikel I), eine Laborwindkanalstudie (Artikel II) und großflächige Feldversuche (Artikel III).

In der Laborscreeningstudie (Artikel I, S. 15ff.) wurde das Agglomerationspotenzial von 14 ausgewählten Proteinen und Polysacchariden aus verschiedenen pflanzlichen und tierischen Quellen auf zwei für den Bergbau repräsentativen Bodentypen untersucht. Die Bodenproben wurden durch Aufsprühen der Biopolymerlösungen präpariert und auf Wasserrückhaltevermögen, den Penetrationswiderstand und Krustendicke hin untersucht. Es zeigte sich, dass alle Biopolymere Bodenpartikel agglomerierten, unterschiedlich dicke Krusten mit deutlich erhöhtem Penetrationswiderstand bildeten und teilweise das Wasserrückhaltevermögen der Proben verbesserten. Der Biopolymertyp und die Konzentration hatten einen signifikanten Einfluss auf die untersuchten Parameter, wobei die Proteine zumeist in höheren Konzentrationen eingesetzt werden mussten, um ähnliche Ergebnisse wie die Polysaccharide zu erzielen. Die Studie zeigte, dass diverse Biopolymere das Potenzial haben, als Staubbindemittel zu wirken, und ermöglichte die Auswahl geeigneter Biopolymere für die nachfolgende Studienphase.

Nachdem in Artikel I das Potenzial von Biopolymeren anhand indirekter Parameter evaluiert wurde, untersuchte die Laborwindkanalstudie (Artikel II, S. 41ff.) die Winderosionsbeständigkeit von Bodenproben, die mit verschiedenen Biopolymeren, Konzentrationen und Anwendungsmengen behandelt wurden, direkt. Zusätzlich wurden Penetrometerversuche durchgeführt, um zu untersuchen, ob eine Korrelation zwischen Winderosion und Penetrationswiderstand besteht. Die Ergebnisse zeigten, dass alle Biopolymere die Winderosionsbeständigkeit der behandelten Proben signifikant verbesserten und im Vergleich zu unbehandelten Proben teilweise eine Erosionsminderung von $>99\%$ erreichten. Der Bodenabtrag nahm mit steigender Konzentration ab, bis ein Plateau erreicht wurde. Die Effektivität der verschiedenen Biopolymere variiert, wobei die Proteine zumeist höhere Konzentrationen benötigten als Polysaccharide, um eine ähnliche Wirkung zu erzielen. Darüber hinaus zeigte die Spearman-Rangkorrelation eine Korrelation zwischen Winderosionsbeständigkeit und dem Penetrationswiderstand, was das Taschenpenetrometer zu einer rapiden und kostengünstigen Methode für die qualitative Bewertung potenzieller Staubbindemittel macht. Die Ergebnisse dieser Studie ermöglichten weiterhin auch die Auswahl geeigneter Biopolymere und Anwendungsparameter für die Feldversuche.

Nachdem die Untersuchungen für Artikel I und II im Labormaßstab und unter Laborbedingungen durchgeführt wurden, untersuchten die groß angelegten Feldversuche (Artikel III, S. 61ff.) die Wirksamkeit von drei ausgewählten Biopolymeren (Maisstärke, Xanthan und Ackerbohnenproteinkonzentrat) unter realen Feldbedingungen. Im August 2022 wurden die Biopolymerlösungen mit einer Feldspritze auf die Versuchsflächen auf der Außenkippe des Braunkohlentagebaus Inden in Deutschland ausgebracht. In den folgenden 45 Tagen wurden auf den Versuchsflächen wiederholt die Staubemissionen gemessen, die von den behandelten Böden durch den von einem Gebläse erzeugten Luftstrom emittiert wurden. Ergänzend wurden visuelle Beobachtungen und Penetrometerversuche durchgeführt. Es zeigte sich, dass alle Behandlungen die durch den Luftstrom verursachten Staubemissionen über einen kurzen Zeitraum (bis zum 8. Tag) signifikant reduzierten. Danach verloren die Behandlungen ihre Wirksamkeit, was wahrscheinlich auf Auswaschungen durch Regen zurückzuführen ist. Die Ergebnisse deuten darauf hin, dass unter trockenen Bedingungen eine größere Beständigkeit erreicht worden wäre. Die Feldversuche lieferten somit den praktischen Nachweis, dass Biopolymere die Staubemissionen auf exponierten Bergbauböden über kürzere Zeiträume wirksam reduzieren können.

Die Synthese der Ergebnisse zeigt, dass eine hohe Winderosionsbeständigkeit (Artikel II) ein guter Indikator für die Wirksamkeit der Behandlungen unter Feldbedingungen (Artikel III) ist und zudem mit dem Penetrationswiderstand (Artikel I und II) korreliert. In Bezug auf die Hauptforschungsfrage kann daher gefolgert werden, dass die in den Feldversuchen – und wahrscheinlich auch die in den Laborversuchen – getesteten Biopolymere, in der Lage sind, windinduzierte Staubemissionen auf Brachflächen des Bergbaus effektiv zu unterdrücken. Da die Feldversuche - im Vergleich zu anderen Studien über Staubbindemittel - mit relativ geringen Auftragsdosen durchgeführt wurden, ist das funktionelle Potenzial der Biopolymere als Staubbindemittel vielversprechend, obgleich Anwendungen mit konventionellen Staubbindemitteln wahrscheinlich beständiger sind. Das Potenzial der einzelnen Biopolymere variiert erheblich, da einige Substanzen wesentlich höhere Dosierungen benötigen, um eine ähnliche Wirkung zu erzielen wie andere. Insgesamt zeigen die Ergebnisse dieser Arbeit, dass Biopolymere eine vielversprechende, effektive, einfach anzuwendende und verfügbare Alternative zu herkömmlichen Staubbindemitteln darstellen. Auch wenn ihre praktische Anwendung wahrscheinlich häufigere Anwendungsintervalle als bei herkömmlichen Produkten erfordert, sind sie biobasiert und gelten als umweltfreundlich. Zukünftige Studien sollten vergleichende Feldversuche mit Biopolymeren und herkömmlichen Staubbindemitteln sowie standardisierte Tests zur Bestimmung der Ökotoxikologie und der biologischen Abbaubarkeit umfassen.

English Abstract

Wind-induced dust emissions from active and abandoned mines pose a significant threat to local ecosystems and workers' health, and affect surrounding communities. They are generated from large, exposed, barren areas, such as tailings dams, dumps, or working benches, and remain challenging to control. This issue will become increasingly important as the footprint of mines and the frequency and severity of droughts and strong wind events are predicted to increase. Using dust suppressants, such as water, salt brines, or petroleum-based and synthetic polymers, is a proven method for dust control on exposed surfaces. However, while the effect of water evaporates quickly, traditional dust suppressants are costly, can have adverse environmental effects, and are not bio-based. As the mining industry is simultaneously challenged to minimise its environmental impacts and meet growing societal expectations, there is a need for low cost, easy to use, readily available, bio-based, and environmentally friendly dust suppressants.

Recently, scholars have explored the potential of using biopolymers to stabilise soils or control dust emissions. Biopolymers are produced by plants, animals, or microorganisms (e.g., starches, cellulose, gelatine, or xanthan gum). However, the potential of diverse polysaccharides and proteins from sources native to continental climates remains under-explored, and their effectiveness to control wind-induced dust emissions has not yet been tested in large-scale field trials. This work addressed these gaps and aimed to answer the Main Research Question: "*What is the potential of polysaccharide and protein biopolymers as dust suppressants for dust control on barren, undisturbed mine soils?*" Therefore, the research of this thesis was divided into three consecutive study phases, the results of which have been published in three corresponding research articles: A Laboratory Screening Study (Article I), a Laboratory Wind Tunnel Study (Article II), and Large-Scale Field Trials (Article III).

The Laboratory Screening Study (Article I, p. 15ff.) evaluated the soil agglomeration potential of 14 selected proteins and polysaccharides from diverse botanical and animal sources on two different mine soils. Soil samples were prepared by spray-on application, and the treated samples' moisture retention, penetration resistance, and crust thickness were investigated. It was found that all biopolymers agglomerated particles and formed crusts of varying thickness, with significantly increased penetration resistances and partially improved moisture retention. Biopolymer type and concentration significantly affected the parameters tested, whereby most proteins required application at higher concentrations to perform similarly to the polysaccharides. The study demonstrated that various biopolymer types display the potential to act as dust suppressants and allowed for the selection of the most promising biopolymers to be studied in the subsequent study phase.

After evaluating the potential of biopolymers based on indirect parameters in Article I, the Laboratory Wind Tunnel Study (Article II, p. 41ff.) directly examined the wind erosion resistance of soil samples treated with different biopolymers, concentrations, and application rates. Complementary pocket penetrometer testing was conducted to investigate whether a correlation between wind erosion and penetration resistance exists. The results showed that all biopolymer treatments significantly improved the wind erosion resistance of the samples, partially achieving dust control

effectiveness $> 99\%$ compared to untreated samples. Soil loss was decreased with increasing concentration until reaching a plateau concentration. The effectiveness achieved by the different biopolymer types varied, with proteins tending to require application at higher concentrations than polysaccharides to achieve similar performance. In addition, the Spearman rank correlation revealed a correlation between wind erosion and penetration resistance, making the pocket penetrometer a rapid, low-cost method for qualitatively evaluating potential dust suppressants. The results of this study further allowed the selection of biopolymers and application parameters for the field trials.

After the studies for Articles I and II conducted tests at laboratory scale and conditions, Large-Scale Field Trials (Article III, p. 61ff.) investigated the efficacy of three selected biopolymers (corn starch, xanthan gum, and fava bean protein concentrate) under real field conditions. The trials started in August 2022 with a field sprayer applying selected biopolymer doses on trial areas located on the overburden dump of the Inden open-cast lignite mine in Germany. Over the following 45 days, the trial plots were repeatedly tested by measuring the dust emissions from soil plots exposed to airflow of an electric fan and were complemented by visual inspections and penetrometer tests. All treatments significantly suppressed the airflow-induced dust emissions in the short term (up to day 8). After that, the effectiveness of the treatments degraded, likely due to rain leaching the biopolymers off the soil surface. The results suggest that the treatments would have lasted longer under dry conditions. Thus, the field trials provided practical evidence that biopolymers can effectively mitigate dust emissions on exposed, undisturbed mine soils in the short term.

The synthesis of the findings showed that a high wind erosion resistance (Article II) proved to be a good indicator of the effectiveness of the treatments at field conditions (Article III) and also correlated with the penetration resistance (Articles I and II). Thus, concerning the main research question, it can be concluded that the biopolymers tested in the field trials, and likely those tested in the laboratory studies, can effectively control wind-induced dust emissions on barren, undisturbed mine soils in the short term. As the field trials tested relatively low treatment doses compared to other dust suppressant studies, the functional potential of biopolymers as dust suppressants is promising, albeit conventional dust suppressant treatments are likely more durable. The dust control potential of the individual biopolymers varies considerably, as some biopolymers require notably higher dosages than others to achieve a similar effectiveness. Ultimately, the results of this thesis demonstrate that biopolymers are a promising, effective, easy-to-use, and readily available alternative to traditional dust suppressants for dust control on barren mine soils. While their practical application will likely require more frequent rejuvenation intervals than commercially available products, they are bio-based and considered environmentally friendly. Future studies should conduct comparative field trials with biopolymers and traditional suppressants and standardised ecotoxicology and biodegradability testing.

Publications Related to This Thesis

Peer-Reviewed Articles:

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Abstracts and Conference Proceedings:

Sieger, J.L., Lottermoser, B.G. and Freer, J. Field trials investigating the effectiveness of biopolymers as dust suppressants on exposed mine soils. In: TERRA, 1st European Conference on Teaching and Research in Sustainable Resource Extraction. TERRA, Boppard, 06–08 September 2023; RWTH Aachen University, Ed., 2023.

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Contributors to This Thesis

Main Contributors and Co-authors:

- *Johannes Lukas Sieger*, the main author of this work, was primarily responsible for the conceptualisation, methodology, investigation, formal analysis, validation, visualisation, original drafting, editing, and overall administration of this thesis and its three associated original research articles.
- *Bernd Georg Lottermoser*, co-author of the research articles and supervisor of this thesis, contributed to all three articles and this thesis. He provided valuable advice and critical feedback on the design and methods of the study phases, as well as on the draft manuscripts of the three research articles. His valuable feedback contributed to improving the quality of the research and the published research articles.
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List of Abbreviations and Acronyms

Notation	Description
Al	Aluminium
ANOVA	Analysis of variance
AR	Application rate (L/m^2)
AT	Austria
BAuA	German Federal Institute for Occupational Safety and Health (german: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin)
C	Control group
Ca	Calcium
C_c	Coefficient of curvature
cf.	Compare (latin: confer)
CH	Fat clay (abbreviation according to unified soil classification system (USCS))
CMC	Carboxymethyl cellulose, polysaccharide
CS	Corn starch, polysaccharide
C_u	Corn uniformity
DE	Germany
df	Degrees of freedom (ANOVA parameter)
DNA	Deoxyribonucleic acid
D_{60}	Particle size diameter (mm) at which 60 % of a soil samples volume have a finer particle-size
e.g.	For instance (latin: exempli gratia)
EICP	Enzyme induced carbonate precipitates
EU	European Union
F	F-value (ANOVA parameter)
F	Force in Newton (N)
FBPC	Fava bean protein concentrate, protein
Fe	Iron
HEA	Hen egg albumen, protein
HG	Haemoglobin protein, protein
i.e.	That is (latin: id est)
ICP-MS	Inductively coupled plasma mass spectrometry
LV	Latvia
M	Mean
m	Mass in gram (g)
Mg	Magnesium
MICP	Microbial-induced carbonate precipitates
ML	Silt (abbreviation according to USCS)
Mn	Manganese
MS	Mean square (ANOVA parameter)

Notation	Description
MT	Mine tailings
n	Sample size
N/A	Not available
Na	Sodium
NL	Netherlands
NLS	Sodium lignosulphonate, polysaccharide
O	Oxide
P	Phosphate
p	P-value (ANOVA parameter)
PES	Pea starch, polysaccharide
PM_{10}	Particulate matter 10 (concentration of inhalable particles with a diameter $\leq 10\,\mu$m in mg/m³)
$PM_{2.5}$	Particulate matter 2.5 (concentration of inhalable particles with a diameter $\leq 2.5\,\mu$m in mg/m³)
PP	Plasma protein, protein
RNA	Ribonucleic acid
RS	Red sand (bauxite residue)
SD	Standard deviation
Si	Silicon
SL	Sandy loam (abbreviation according to USCS)
SM	Sand with silt (abbreviation according to USCS)
SP	Poorly graded sand (abbreviation according to USCS)
SP-SM	Poorly graded sand with silt (abbreviation according to USCS)
SS	Sum of squares (ANOVA parameter)
T	Thicknes in millimeter (mm)
t	Time in hours (h), minutes (min), seconds (s), days (d)
TG	Technical gelatine, protein
Ti	Titanium
TSP	Total suspended particles (mg/m³)
U.S. EPA	United States Environmental Protection Agency
USCS	Unified soil classification system
USD	US-Dollar
v	Air velocity (m/s)
WHO	World Health Organization
WP	Wheat protein, protein
WPC	Whey protein concentrate, protein
WS	Wheat starch, polysaccharide
XG	Xanthan gum, polysaccharide
XRD	X-ray diffraction
XRF	X-ray fluorescence spectroscopy
Δm_{BP}	Total soil loss of biopolymer-treated sample (g/m²)
Δm_C	Total soil loss of control group C (g/m²)
α	Significance level of ANOVA

Chapter 1

General Introduction

The Earth is in the epoch of the Anthropocene (*greek: recent age of man*), the – still unofficial – geological period in which humanity started to have a substantial impact on the Earth's ecosystems: lithosphere, hydrosphere, atmosphere, biosphere, pedosphere, and cryosphere. Many of humanity's impacts are related to the pollution of sensitive ecosystems, mainly through the transport pathways: air, water, soil, and biota [4]. The transport of suspended dust through the air poses distinct challenges and hazards to human health and ecosystems. Entrainment and transport of atmospheric dust occurs rapidly over vast aerial extents, is hardly confined by topographic boundaries, and once dispersed, the forces of nature – wind and rainfall – determine the time and place of its deposition [4]. Since air is humanity's breathing medium and particulate matter is often hardly visible, unintentional ingestion is challenging to control. While natural dust emissions are a phenomenon as old as the world, it is anthropogenic dust that causes exceptional harm to ecosystems and human health.

Of the different anthropogenic mineral dust sources, particulates from the mining industry pose the greatest risk to human health and the environment [4]. While not all mine dust emissions per se pose a threat to human health or ecosystems, it is typically dust with elevated concentrations of particulate matter (PM), crystalline silica (e.g., quartz) and coal, or metals and metalloids (e.g., arsenic (As), cadmium (Cd), lead (Pb)) that affect the health of workers, communities, and local ecosystems [4–6]. Among workers, dust overexposure may cause diseases such as pneumoconiosis or silicosis [6]. Mine communities are primarily affected by nuisance dust, but there is evidence that their health, particularly that of children, is also affected by mine dust [6–8]. Regarding ecosystems, mine dusts have been shown to reduce biodiversity, affect plant growth, and contaminate water and mine soils [8–11]. The impacts of mine dust will inevitably increase in the coming decades as mineral resource extraction is projected to increase, and the effects of climate change will increase the frequency and severity of droughts and strong wind events in many regions of the world [12]. While the need for mineral raw material extraction is undisputed, mine operators are responsible for controlling dust emissions to minimise the impacts on workers, communities, and ecosystems.

Mine dusts are continuously generated in large quantities at any mine site [4], either by mechanical impacts or wind erosion processes. Mechanically generated dust is caused by impact, friction and abrasion along the stages of primary raw material extraction (e.g., drilling, loading, conveying, or crushing), and there are various established engineering controls such as encapsulations, dust filters, or water spray systems [13]. In contrast, the control of dust emissions generated by wind erosion from exposed, undisturbed surfaces, such as tailings dams, dumps, or working benches, remains challenging due to their vast areal extent.

The use of dust suppressants is a proven method for mitigating dust emissions from such exposed

surfaces. Dust suppressants are sprayed on dust-prone soils and act by agglomerating soil particles, increasing the soil's wind erosion resistance and thus reducing the generation of dust emissions. However, many conventional dust suppressants, such as salt brines, petroleum-based products or synthetic polymers, are costly, can have adverse environmental effects, and the toxicity of the (often proprietary) formulations is often insufficiently studied [14, 15]. In addition, the constituents of most synthetic polymers are still predominantly produced by the petrochemical industry from fossil fuels, resulting in an increased carbon footprint. Therefore, bio-based, cost-effective, environmentally friendly dust suppressants are needed to progress towards more environmentally benign dust control practices at mine sites.

In soil stabilisation and dust control research, scholars have lately increasingly explored the potential of using biopolymers to improve soil mechanical properties to meet specific engineering needs. Biopolymers are produced by living organisms, such as plants, microbes, and animals, are biodegradable and can be regionally sourced in most regions of the world. Biopolymers, therefore, may have the potential to become environmentally friendly, bio-based alternatives to traditional soil stabilisers and dust suppressants. However, most published research studied their application potential as soil stabilisers, while only a few studies have investigated their potential as dust suppressants. Several research gaps must be addressed to better evaluate and investigate their potential as dust suppressants. For instance, their application has not yet been tested in large-scale field trials under real field conditions, and only a limited variety of biopolymers have been tested for their potential as a dust suppressant.

This dissertation addresses these research gaps and seeks to answer the following main research question: *What is the potential of polysaccharide and protein biopolymers as dust suppressants for dust control on barren, undisturbed mine soils?*. By investigating the functional potential of biopolymers as dust suppressants on barren mine soils, the results of this thesis will be significant for the evaluation and advancement of environmentally friendly dust control practices. The thesis will add to the existing body of knowledge by evaluating diverse biopolymers regarding their potential to agglomerate soil particles and improve soil wind erosion resistance. In addition, the research will reveal whether biopolymer treatments can effectively mitigate wind-induced dust emissions when applied on a large scale under real field conditions. Ultimately, this work will contribute to progress towards more environmentally friendly dust control practices and reduce barriers opposing broader adoption by operators.

In the following, this chapter first provides the background relevant to the understanding of this thesis (section 1.1), followed by a concise review of the state of research on biopolymers as dust suppressants and soil stabilisers (section 1.2). Based on this review, the research gaps (sections 1.3) and the *Main Research Question* and *Objectives* of this thesis are deduced (section 1.4). Thereafter, section 1.5 introduces the overall methodology and structure of this cumulative dissertation and section 1.6 highlights the significance of this work.

1.1 Background

This subchapter introduces the background and concepts relevant to this thesis. It defines the term 'mine dust' and discusses its potential health and environmental impacts, introduces the mechanisms of wind erosion and dust generation, as well as the factors that influence the wind erosion resistance of a soil. After that, dust suppressants and their different categories are explained, followed by a brief discussion of the differences between the related disciplines of dust control and soil stabilisation. This is important for the context and understanding of the review section (section 1.2), which analyses the state of research on biopolymers in soil stabilisation and dust control. Before the review section, a brief introduction to biopolymers is given in section 1.1.6. A Glossary (p. 129ff.) has been compiled at the end of this thesis and contains several further definitions relevant to the understanding of this thesis.

1.1.1 Mine Dust

A detailed definition of the term *dust* and related terms such as *fugitive dust*, *total suspended particles (TSP)*, *particulate matter (PM)*, *nuisance dust*, or *anthropogenic dust*, can be found in the Glossary (p. 129ff.) of this thesis. This section focuses directly on mine dust:

In the context of this thesis, the term *mine dust* is defined as the entirety of anthropogenic dust emissions generated at mine sites. Based on this definition, mine dust is predominantly composed of mineral dust (mineral solids) but inevitably contains marginal fractions of organic and synthetic constituents (e.g., tyre abrasion). While most dust emissions at mine sites originate from the operation itself, they may also include resuspended dust from surrounding areas. The composition of mine dust's mineral solid fraction depends on the mineralogy of the mined raw materials. For example, mine dust generated in quarries and most hard rock mines is primarily composed of silicates (i.e., quartz, feldspar and phyllosilicates) and carbonates (i.e., calcite and dolomite) [16]. Mine dusts can pose a high risk to human health and the environment if they are rich in crystalline silica (e.g., quartz), coal or contain metals and metalloids (e.g., As, Pb, Cd, U, Hg, or Cr) [4, 5]. These contaminants are often concentrated in finer particle size fractions [4]. A review of the potentially toxic elements in metalliferous mine dusts and their common bearing mineral phases has been published by Entwistle et al. [6] and is recommended for further reading. Dust is commonly classified by its size (i.e., aerodynamic diameter), and emissions are typically monitored by inexpensive passive samplers (e.g., dust deposition gauges) or continuously by powered, active analysers (e.g., aerosol spectrometers).

Among anthropogenic dust emissions, mine dusts are notable for the quantity of particulates generated, the global extent of the area impacted, and the potential for toxic contaminants associated with the emissions [4]. Mine dust can have significant impacts on ecosystems, occupational and public health, and the social acceptance of an operation. In this regard, reviews by Entwistle et al. [6], Noble et al. [5], Plumlee and Ziegler [17], Csavina et al. [4], and Yu et al. [18] provide comprehensive overviews. The following paragraphs provide a brief summary of the potential health, environmental and community impacts that have been associated with mine dust emissions. Before doing so, it is important to emphasise that the potential effects of mine dust are highly dependent on their particle size, shape, and chemistry. Not all mine dusts cause serious health effects, and understanding their mineralogy and geochemistry is essential to assessing and managing their potential hazards [5].

Occupational health effects. Occupational overexposure to mine dust is considered one of the most severe causes of occupational cardiovascular and respiratory diseases. The potential health effects of dust are related to the particle size, chemistry, shape and bioaccessibility of the dust [6, 10], as well as the frequency, intensity and duration of exposure [5]. Fibrogenic mine dust (e.g., crystalline silica, coal, asbestos, talc, kaolin, bentonite and feldspar) can cause pneumoconiosis [19–23], chronic obstructive pulmonary disease (COPD) [20], tuberculosis [8], asthma [24], lung cancer [22], and other respiratory health effects [25, 26]. These diseases impair lung function, and pneumoconiosis can even be fatal. Metalliferous mine dust, containing potentially toxic elements, such as As, Cd, and Cr, are known carcinogens, can impair mental and nervous system function, and may cause DNA or organ damage [4]. Other diseases associated with metal overexposure include chronic neurological disorders and kidney and liver damage [6].

Community acceptance and health. Communities living near mine sites often perceive mine dust primarily as an aesthetic nuisance, as it deposits on and pollutes their property, cars, or laundry. Due to their distinctive colour, this especially applies to coal and iron ore dust [27] and can negatively affect the community acceptance of an operation. However, mine dust may also affect community health, either directly through inhalation or indirectly through contamination of water sources or agricultural land. While several studies have examined the impact of mining operations on communities, it is often impossible to isolate the contribution of mine dust, as many

communities are also exposed to other sources of pollution, such as smelter fumes. Leuenberger et al. [7] and Antabe et al. [28] conducted extensive surveys among mining communities, with Leuenberger et al. reporting that many participants considered mine dusts to be deterring the maintenance of hygienic conditions, causing respiratory diseases and sometimes eye infections. Other studies have linked increased contaminant exposure of mining communities to wind erosion and dust emissions from nearby abandoned mine dumps [29] and tailings dams [30–32]. Further studies reported elevated Pb levels in mining cities' indoor dust [33–35]. Another study found elevated Pb and Cd concentrations in the urine and faeces of children living near a long-abandoned Pb-Zn mine, which the authors linked to dust emissions from the nearby mine dumps [8, 36].

Environmental impacts. Mine dust not only pollutes the atmosphere but also affects other environmental spheres, including soil, water, flora and fauna. For example, Mwaanga et al. [8] reported contaminated soils around an abandoned PbZn mine and pathological lead poisoning of mammals. Pal and Mandal [9] linked dust emissions from quarrying to environmental impacts on a river basin area, reporting channel bed aggradation, increased water sediment load and degraded water quality. Middleton et al. [37] reported widespread elevated concentrations of As in residential soil and dust in regions surrounding historic mine sites in Cornwall. Battogtokh et al. [38] attributed the metal contamination of soils near the tailings dam of the Erdenet copper-molybdenum mine to wind-blown dust emissions. Finally, mine dust has also showed to impair the morphology, physiology, photosynthesis, and nutritional value of plants [11].

Legislative bodies, such as the World Health Organization (WHO) [39], the European Union (EU) [40] and the United States Environmental Protection Agency (U.S. EPA) [41] have developed extensive legislation and standards on air quality monitoring and defined exposure limits for various pollutants. In addition, institutions such as the Federal Institute for Occupational Safety and Health (DE, BAuA) provide specified documentation on workplace exposure limits, such as for hazardous substances (TRGS 900), wood dust (TRGS 553) or silica dust (TRGS 559).

1.1.2 Wind Erosion and Dust Generation

Mine dust emissions are generated by either mechanical impact or wind erosion processes [42]. Mechanically generated dust is produced by particle size reduction resulting from impact, friction and abrasion that inevitably, and sometimes intentionally, occur during all stages of raw material extraction (drilling, blasting, loading, conveying, crushing, grinding, and unpaved road traffic). Various established control methods for these emissions exist and have been comprehensively presented by Cecala et al. [13] but are outside the scope of this thesis. Instead, this dissertation focuses on the control of wind-induced dust emissions, which typically occur on barren, topographically exposed soil surfaces without vegetative cover, such as working benches, slopes, overburden and waste dumps, stockpiles, and tailings dams and beaches.

Wind erosion is the process of particle entrainment, transport and deposition by wind [43]. Particle entrainment (detachment) occurs when the aerodynamic drag and lift forces (i.e., the friction velocity) of the wind acting on a soil surface exceed the gravitational and inter-particle cohesion forces resisting particle removal (i.e., the threshold friction velocity of a soil) [44]. The threshold friction velocity describes the capacity of a surface to resist wind erosion and depends on several soil surface properties, explained in section 1.1.3. Particle detachment occurs through impact and abrasion by already detached rolling or bouncing particles. Depending on the particle size, wind erosion exhibits the particle movement modes *Creep*, *Saltation* and *Suspension* [16, 43] (cf. Glossary, p. 129ff.).

Creep and saltation play an important role in wind erosion and the generation of dust emissions, as these two mechanisms cause the abrasion and suspension of dust-sized particles into the atmosphere [4]. For the wind erosion of sand particles, the balance between aerodynamic and gravitational forces is the key determinant. By contrast, for dust-sized particles with $d < 20\,\mu m$,

the effect of the gravitational forces diminishes, and instead, the inter-particle cohesive forces become the key determinants. As a result, the actual dust emission mechanisms differ from those of the wind erosion mechanisms. Shao [44] proposed three dust emission mechanisms: *Aerodynamic entrainment*, *Saltation bombardment* and *Disaggregation* (cf. Glossary, p. 129ff.). Depending on the dust particle characteristics and atmospheric conditions, entrained dust particles can rapidly travel distances on a local scale of a few metres or a global scale until they are finally deposited by dry or wet deposition [4, 44].

1.1.3 Wind Erosion Resistance

To reduce wind erosion and the associated dust emissions from a given soil, it is necessary to reduce the aerodynamic forces acting on it or to increase the soil's wind erosion resistance. The former can be achieved by installing wind fences and barriers or increasing soil roughness. Soil roughness can be increased by raising beds perpendicular to the prevailing wind direction or by placing non-erodible objects, such as gravel or landscaping stones, which absorb some of the wind forces, reduce the wind shear stresses acting on the soil, and limit the cascading effects of saltation [16, 43]. Regarding particle size and texture, soils with a higher clay and silt content are less susceptible to wind erosion because clay minerals absorb more water than sand particles [16], with moisture holding the particles together by capillary forces [16, 45]. Other cohesive forces affecting wind erosion resistance include van der Waals, electrostatic and chemical bonding forces [44]. Establishing a vegetative cover is usually the best and most effective means of increasing soil erosion resistance [43]. It increases surface roughness and improves soil texture, water content and compaction through root systems and vegetation litter [46, 47].

However, for many areas on mine sites commonly susceptible to wind erosion and associated dust emissions, installing wind barriers, increasing soil roughness, or establishing and maintaining vegetation cover is often not feasible for operational or budgetary reasons or due to unfavourable soil properties. In addition, sometimes, only temporary control solutions are required. In such cases, the only remaining alternative to reduce wind erosion and associated dust generation is to improve the wind erosion resistance of the soil by applying dust suppressants.

1.1.4 Dust Suppressants

Dust suppressants, often also referred to as dust palliatives, surfactants or dust control products, are substances used to control particulate matter emissions from trafficked soil surfaces, such as unpaved roads or untrafficked (undisturbed), barren areas prone to wind erosion [14, 48]. They are used at mine sites, on unpaved rural roads, at solar farms, or by the military to control emissions from airfields, roads, helipads, and base camps [49, 50]. Dust suppressants typically come as liquid concentrates and are diluted to the desired concentration in water. They are applied via spray-on or mix-in (also termed admix) application [50]. Compared to spray-on, the mix-in application typically results in a more durable, long-term dust control and requires less frequent rejuvenation intervals [48]. Dust suppressants act either by hygroscopicity, agglomeration, or both mechanisms simultaneously [51]. Hygroscopic suppressants absorb moisture from the surrounding atmosphere, increasing soil moisture. Agglomeration is the process of binding smaller particles together into larger granules, achieved by increasing the inter-particle cohesion between particles of the soil matrix [51].

There are different types of dust suppressants that can be used for dust control on undisturbed or trafficked barren soils. Several guidelines for the selection and application of dust suppressants have been published by academics [48, 50, 52–54], with Bolander and Yamada [54] and Jones [48] providing the most comprehensive works. While these guidelines focus primarily on unpaved roads, much of the content is applicable to dust control on undisturbed areas. The existing literature on dust suppressants typically distinguishes between seven categories [54]: *water*, *salts and*

brines, *synthetic polymer products*, *organic non-petroleum products*, *organic petroleum products*, *concentrated liquid stabilisers* and *clay additives*. In addition, *bio-mineralisation* constitutes a rather novel dust control approach that may be assigned its own category:

1. *Water* is the world's oldest and most widely used dust suppressant due to its low cost, high availability, and ease of application. However, it provides only very short-term dust control, as its effect vanishes rapidly as it evaporates, especially in hot climates, so frequent rejuvenation intervals – often multiple per day – are needed.

2. *Salts and brines* consist mainly of calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), and sodium chloride (NaCl). Due to their hygroscopicity, they absorb moisture from the atmosphere, which agglomerates fine particles and aggregates the soil matrix by capillary suction forces [48]. They are produced from natural salt brines, seawater evaporation or as a by-product of industrial processes (e.g., ammonia soda) and are still commonly used due to their effectiveness and durability. However, their use can lead to elevated chloride concentrations in streams near their application sites, potentially contaminating local groundwater and affecting plant growth and aquatic life. Furthermore, they can cause corrosion of vehicles trafficking treated areas.[14].

3. *Synthetic polymer products* are mostly proprietary mixtures of different synthetic polymers (e.g., polyvinyl acetate, ethylene, vinyl ester, or vinyl acrylic) suspended in an aqueous phase by surfactants [14, 50]. While these products are highly effective and durable, they are comparatively expensive and have potentially adverse environmental effects. The environmental impact of many available products from different manufacturers has been studied insufficiently by independent parties, and their composition remains proprietary [15]. In addition, the constituents of most synthetic polymers (e.g., ethylene (C_2H_4)) are still almost exclusively produced from petroleum derivatives [55]. Fossil-free production pathways for these constituents do exist, such as ethylene from bioethanol, but they represent only a small fraction of global production and are more costly [56, 57].

4. *Organic non-petroleum products* traditionally include plant-based substances such as glycerine, molasses (e.g. [58, 59]), vegetable oils, tall oil pitch, and lignosulphonates. Complementary to these substances, Freer et al. [60–62] have recently demonstrated the dust suppressant potential of other food processing by-products and wastes, such as different types of vinasses and permeates. These products are plant-based and often by-products, so their composition is variable. Organic non-petroleum products mostly act by increasing the inter-particle cohesion and agglomerating particles. Most of these substances are water soluble and biodegradable, so they typically require more frequent rejuvenation intervals than brines, petroleum and synthetic products [48].

5. *Organic petroleum products* are derived from petroleum refining and include asphalt emulsions, cutback solvents, mineral oils, petroleum resins, and tars [14, 48]. These substances are highly effective and extremely durable as they are insoluble in water and are not biodegradable. However, these products are associated with the highest environmental impact of all dust suppressants, as they contain toxic and carcinogenic compounds, so some agencies, such as the U.S. EPA, have banned their use [14].

6. *Concentrated liquid stabilisers* (e.g., sulphonated oils) have proprietary compositions and only limited published information. Sulphonated oils are only suitable for soils with higher clay content and act by electrochemical or enzymatic cementing bonds, rendering the clays hydrophobic, displacing the adsorbed and hydration water and forming an oily protective layer around the particles. In addition, the treatments reduce air voids in the soil, improving soil compaction and erosion resistance [14, 48]. As little information is available on these products, they are presumably rarely used.

7. *Clay additives* such as bentonite, montmorillonite or other local clays can improve the erosion resistance of soils with low fine content and plasticity [48]. However, they must be thoroughly mixed into the soil and often provide insufficient dust control to be considered real dust suppressants [48]. Due to these limitations, they are not frequently used for dust control.

8. *Bio-mineralisation* is a relatively novel dust control and sand stabilisation method that has lately received increasing attention from researchers and is mainly divided into enzyme- and microbially-induced carbonate precipitation (EICP or MICP)[63–70]. MICP involves treating the soil with a cementing solution consisting of bacteria, urea (CH_4N_2O) and calcium ions (Ca^{2+}). The bacteria produce urease enzyme, which hydrolyses urea in the presence of calcium ions, precipitating calcium carbonate ($CaCO_3$) crystals in the soil pore space, cementing particles together and forming a wind erosion resistant crust [66, 71]. In the case of EICP, the urease enzyme is added directly to the cementing solution. However, the bio-mineralisation method has several limitations: it requires specific growth conditions for effective cultivation and application, it performs poorly in fine soils [72, 73], and it produces ammonium ions (NH_4) as a by-product, which increases the soil pH [74, 75].

In summary, *clays*, *concentrated liquid stabilisers* and *organic petroleum products* are today rarely used for dust control. Instead, due to their high *effectiveness* and *durability* (cf. Glossary), *synthetic polymers* and *salt brines* are the most widely used dust suppressant categories, aside of *water*. However, as outlined in the previous sections, their use can be associated with adverse environmental impacts. This has recently led to increased research efforts into potentially more environmentally friendly dust control products, such as *biopolymers*, *food processing wastes and by-products*, and *bio-mineralisation*. A detailed introduction and review of biopolymers, the main scope of this thesis, is the subject of sections 1.1.6 and 1.2.

1.1.5 Differences Between Dust Control and Soil Stabilisation

As a prelude to the review chapter, it is crucial to point out the differences and similarities between soil stabilisation (soil stabilisers) and dust control (dust suppressants). A general definition of *soil stabilisation* can be found in the Glossary (p. 129ff.). The two disciplines have in common that they involve the application of substances to soils to achieve a specific engineering purpose. The sole objective of dust control is to reduce particulate matter emissions (fines preservation) from dust-susceptible soils, mainly by spray-on applications with dust suppressants. Instead, the primary goal of soil stabilisation is to maintain or improve the stability of weak soils to achieve desired engineering objectives by chemical, physical, biological, mechanical, or combined techniques (cf. Glossary, [76]), with dust control often being a positive side-effect of their treatments. Soil stabilisation is usually achieved by the more costly, but also more durable, mix-in application of soil stabilisers and some of the suppressants introduced in section 1.1.4 can also be used for it. Thus, the differences between dust control and soil stabilisation ultimately lie within the applications' engineering purpose, the method of application (mix-in/spray-on), and the treatment dosage.

1.1.6 Biopolymers

Biopolymers are biodegradable polymers produced by biological organisms – plants, animals, and bacteria – and can be categorised into polysaccharides, proteins, and polynucleotides based on their composing monomers [69]. Polysaccharides are polymeric carbohydrates composed of hundreds to thousands of repeating saccharide units linked by glycosidic bonds. They are derived from plant cell walls, seeds, grains, tree exudates, algae, bacterial fermentation, and some animals [77]. Cellulose derivatives (cell walls in plants) and starches are the world's most abundant and relevant polysaccharides [77]. Proteins (polypeptides) are composed of repeating units of amino

acid linked by peptide bonds. They are derived from animals (e.g., milk, meat, egg, and gelatine) and botanical sources (e.g., wheat, beans, potatoes, soya, and peas)[77]. Polynucleotides are composed of nucleotides, with deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) being the most popular representatives. For industrial and commercial products, polysaccharides and proteins are the most relevant biopolymer categories [77].

Biopolymers are used in diverse industries, including medicine, packaging, food products and geotechnical engineering. Their functional properties depend on their molecular structure, which is a function of the biopolymer source and the processes used to extract and produce the final biopolymer. For this thesis, polysaccharides and proteins belonging to the group of hydrocolloids are of key interest. Dissolved in water, these hydrocolloids form viscous solutions at low concentrations. Due to their rheology-modifying properties, they are used as thickeners, gelling agents, stabilisers or emulsifiers in food, packaging, adhesives, and other industries [78]. Because of these properties, researchers have recently increasingly explored the potential of these biopolymers in soil stabilisation and dust control.

1.2 Review - Research on Biopolymers as Dust Suppressants and Soil Stabilisers

This section reviews the state of research on the use of biopolymers in soil stabilisation and dust control. Soil stabilisation is included because of its parallels with dust control and because most of the previous research on the use of biopolymers to improve soil properties was dedicated to soil stabilisation. Ancient cultures already used biopolymers, such as animal glues, tree exudates or blood, to stabilise soils and, for example, improve their resistance against rainfall [79]. Over the last centuries, their use in earthen structures has been largely replaced by more durable and potent cementitious binders, such as gypsum, lime, and cement [73]. However, in light of climate change and the significant greenhouse gas (GHG) emissions associated with cement production, researchers started to investigate more environmentally friendly alternatives [80]. While most published research in this area is dedicated to using biopolymers as soil stabilisers, some studies have also investigated their potential as dust suppressants. Several comprehensive reviews summarise the current state of research on biopolymers in soil stabilisation (e.g., Fatehi et al. [81], Moghal and Vydehi [82], Chang et al. [80], Chang et al. [73], Huang et al. [83], Mendonça et al. [84], Choi et al. [69], Jang [85]). The following review focuses on common test methods, the key findings, and the different types of soils and biopolymers tested in the past.

1.2.1 Common Test Methods and Key Findings

Depending on the scope and objective, previous research performed different types of test work to investigate biopolymers' potential as soil stabiliser or dust suppressant. The following two paragraphs provide a condensed overview:

In the field of soil stabilisation, most previous studies have used standard soil mechanical tests to investigate the effects of different parameters such as biopolymer type, concentration, or curing time on soil properties. The studies demonstrated biopolymers' potential to increase unconfined compressive strength [86–88], triaxial shear strength [89–92], tensile strength [93], moisture retention [94, 95], resistance to water erosion [96–99] and repeated wet-dry cycles [74, 100], and to decrease permeability [89, 101–103] and compressibility [104]. To study the underlying stabilisation mechanisms, the test programmes were often accompanied by microstructural analysis via scanning electron microscopy (e.g., [101, 105]). Most studies exclusively conducted laboratory studies, with very limited studies performing field trials [73, 106, 107].

Research on dust suppressants has been dedicated to investigating the ability of biopolymers to improve soil moisture retention, agglomerate particles, and increase the soil's wind erosion

resistance. Laboratory and pocket penetrometer tests have shown that the crusts of biopolymer-treated soil samples have significantly improved penetration resistance [108–116]. Some studies measured the crust thickness of soil samples [110, 111, 113, 114], and others reported increases in soil moisture retention capacity [112–114, 116]. Laboratory wind tunnel studies have shown that biopolymer treatments increase the wind erosion resistance of soil samples [111–114, 116–118], with some studies also reporting increased resistance to repeated wet-dry cycles [111, 112, 118]. While most studies exclusively conducted laboratory studies, only very few field trials were performed, with lignosulphonates being the only biopolymer tested at field conditions [119–121]. These field trials mainly investigated the effectiveness of different suppressants by measuring the particulate matter emissions of soil plots exposed to wind blow. Thus, as also highlighted by several researchers [73, 81, 122], the lack of studies investigating biopolymer treatments at field conditions remains a major gap in soil stabilisation and dust control research.

1.2.2 Soil Types Tested

In soil stabilisation, researchers have investigated the effect of biopolymer treatments on different types of well- and poorly-graded sands [74, 97, 106, 123–126], silts [127–129], clays with low and high plasticity [99, 125, 130–135], different mine tailings [136, 137], bauxite residues [138], and gypseous soils [91, 139]. Researchers found different biopolymer-soil adhesion mechanisms for sands and clays [81]. While on sandy soils, biopolymers act by coating the sand particles and forming a 3D network between the coated particles, biopolymer-clay interactions are more complex. This is because biopolymers interact directly with the clay particles due to the presence of electrical charges and form chemical bonds through electrostatic interactions, hydrogen bonding, ionic bonds and van der Waals forces. As a result, biopolymer treatments are generally expected to have a greater effect on the stability of clayey soils than on sandy soils [81, 84].

In the context of studies on dust suppressants, researchers have tested the application of biopolymers mainly on bauxite residues [108, 109, 113, 114, 117], mine tailings [121, 140, 141], different types of sand [64, 111, 112, 142–144], silt [118], and coal [145]. As dust suppressants are primarily applied as spray-on applications, the particle size distribution of the soil significantly affects the infiltration depth achieved by a typically more viscous biopolymer solution.

1.2.3 Biopolymer Types Tested

In soil stabilisation, most of the research studying the potential of biopolymers has focused on polysaccharides. Due to their unique rheological properties, xanthan gum (e.g., [101, 105, 132, 133, 146]) and guar gum (e.g., [104, 136, 147–149]) are by far the most intensely studied biopolymers, with review articles dedicated to them [82, 150]. Other polysaccharides studied include different tree gum exudates (acacia gum [151], locust bean gum [88, 136, 137], persian gum [152], cassia gum [137]), cellulose derivatives (lignosulphonates [153] and carboxymethylcellulose [86, 136]), algal polysaccharides (agar gum [154–156], sodium alginate [157], and carrageenan [99, 158, 159]) as well as pectin [139], β-glucan [74, 106, 124, 134], gellan [88, 100, 125, 160], starches [106, 161], and chitosan [90, 98, 130, 162]. In contrast to polysaccharides, few studies have investigated protein applications, presumably due to their relatively high cost [51]. The only proteins tested are the bovine milk protein casein [91, 128, 158, 163, 164], bovine blood plasma [165], and the plant protein from maize (zein) [87].

Studies investigating the potential of biopolymers as dust suppressants have examined the polysaccharides xanthan gum [112, 114, 116–118, 141], guar gum [108, 111, 114, 116, 117, 144, 166], lignosulphonate [109, 119, 120, 153], acacia gum [110, 142], pectin [110, 142], sodium alginate [64, 110, 142, 144], carrageenan [118], carboxymethylcellulose [111, 112], starch [167–169], and chitosan [170]. Soybean [171] and collagen derivatives [169, 172] are the only proteins tested.

Thus, regarding the types of biopolymers studied, previous research has focused mainly on

polysaccharides (particularly xanthan and guar gum), with only a few studies investigating proteins. Furthermore, many of the biopolymers investigated come from botanical sources that are native to tropical, arid, and partially temperate climates (e.g., guar gum, persian gum, acacia gum, and locust bean gum) or can only be cultivated in marine environments (e.g., agar gum, carrageenan, and sodium alginate). Only a limited body of research has investigated biopolymer sources that can be easily cultivated in large quantities in many world regions (e.g., starches and cellulose derivatives). Moreover, studies investigating the potential of proteins are underrepresented. In addition, some of the biopolymers studied so far are only soluble in alkaline (casein [128]) or acidic (chitosan [90]) solutions, while others are only soluble in hot solutions (agar gum $>85\,°C$ [155] and gellan $>80\,°C$ [100]). Finally, there are only few comparative studies investigated diverse biopolymers and applications at different application rates and concentrations.

1.3 Research Gaps

The review revealed several research gaps that need to be addressed in order to contribute to a more comprehensive evaluation of biopolymers' potential and effectiveness as dust suppressants. The following list presents the identified research gaps that shall be addressed throughout the thesis research:

1. *Limited variety of biopolymers tested.* Previous research has mainly focused on a few selected polysaccharide biopolymers, particularly xanthan and guar gum. Few studies investigated proteins. Thus, there is a need to investigate the dust suppressant potential of a diverse range of selected, under-represented polysaccharide and protein biopolymers.
2. *Lack of studies investigating biopolymers regionally available in continental climates.* Following up on the first research gap, previous research has primarily investigated biopolymers from botanical sources native to tropical, arid, and partly temperate climates. This hinders the possibility of regional sourcing in regions with continental climates, such as Central and Eastern Europe. In addition, many of the biopolymers studied cannot be easily produced in large quantities, unlike starches and cellulose derivatives, whose potential remains underexplored. Thus, there is a need to focus on biopolymers that can be regionally sourced in regions with continental climates that can be easily cultivated in bulk.
3. *Lack of focus on easy-to-use biopolymers.* Several biopolymers studied so far are only soluble at high temperatures ($>80\,°C$) or in acetic or alkaline solutions. However, to promote potential adoption, emphasis should be placed on biopolymers readily soluble in water to facilitate easy operational integration.
4. *Lack of comparative studies.* Existing studies have mainly performed extensive trials with one or a few biopolymers, often only testing a few different application rates and concentrations.
5. *Lack of field trials.* While several laboratory studies have examined the potential of biopolymers as dust suppressants, there is a lack of large-scale field trials testing the effectiveness and scalability of their applications under real field conditions. This is essential if progress is to be made towards large-scale commercial implementation.

1.4 Research Aim, Question and Objectives

On the basis of the identified *Research Gaps*, an overarching *Research Aim* and a corresponding *Main Research Question* have been deduced. Based on the *Main Research Question*, three successive *Research Objectives* have been derived, each to be achieved by a dedicated study phase and a corresponding research article. Jointly, the findings of the three consecutive research articles shall enable the *Main Research Question* to be answered and achieve the *Research Aim*.

Research Aim:
This thesis aims to investigate the potential of polysaccharide and protein biopolymers as dust suppressants on barren, undisturbed mine soils.

Main Research Question:
What is the potential of polysaccharide and protein biopolymers as dust suppressants for dust control on barren, undisturbed mine soils?

For answering the *Main Research Question*, the experimental work of this thesis focuses on investigating the functional potential of biopolymers to act as dust suppressants. Therefore, three successive laboratory and field study phases will investigate how effective treatments with different biopolymer types and application parameters are in improving specified soil parameters relevant for dust control. A biopolymer treatment is deemed *effective* if it improves the relevant soil parameters tested compared to water or untreated controls. The higher the *effectiveness*, the higher is the functional potential of the biopolymer (cf. definitions of *effective*, and *effectiveness* in the Glossary, p. 129ff.).

Research Objectives:

Article I: Laboratory Screening Study - Research Objective I:
Evaluate the soil agglomeration potential of a diverse selection of underexplored polysaccharide and protein biopolymers on mine soils by testing specific soil parameters important for their functional potential to act as a dust suppressant.

Article II: Laboratory Wind Tunnel Study - Research Objective II:
Investigate the dust suppressant potential of selected biopolymers in a laboratory wind tunnel study, analysing the wind erosion and penetration resistance of mine soil samples treated with different biopolymer types and application parameters.

Article III: Large-Scale Field Trials - Research Objective III:
Investigate the dust suppressant potential of selected biopolymer treatments in large-scale field trials on barren mine soils, analysing their effectiveness in suppressing airflow-induced dust emissions under real field conditions.

While the experimental work of this thesis focuses on investigating the functional potential of biopolymers to act as dust suppressants, further criteria, such as the economics, availability, ease-of-use and environmental friendliness, must also be considered for a comprehensive evaluation of their dust control potential. Therefore, the discussion sections of the research articles and the general discussion chapter of this thesis will also focus on these criteria.

1.5 Structure and Methodology

For each *Research Objective* a dedicated experimental study was conceptualised. The flowchart in Figure 1.1 provides an overview of the overall structure of the thesis and, for each study phase, provides a summary of the scope, materials, and parameters, including a simplified illustration of the test methods to be performed. The results and findings of each study phase have been prepared and published as research articles in peer-reviewed academic journals. Collectively, the synthesis of the results of the research articles shall allow answering the overarching *Main Research Question*.

Now that **Chapter 1** has provided the **General Introduction** to this thesis, **Chapter 2** contains **Article I: Laboratory Screening Study** (p. 15ff.). This study phase evaluated the soil agglomeration potential of a diverse range of selected protein and polysaccharide biopolymers by performing moisture retention, penetration resistance, and crust thickness measurements on biopolymer-treated soil samples. The parameters tested are relevant to infer the functional potential of biopolymers to improve soil wind erosion resistance and act as dust suppressants. Based on the results of this study, proteins and polysaccharides with a high dust suppressant potential were selected for the second study phase.

Chapter 3 contains **Article II: Laboratory Wind Tunnel Study** (p. 41ff.), which investigated the wind erosion and penetration resistance of soil samples treated with different biopolymer types, concentrations, and application rates. While the first study phase measured parameters that indirectly indicate the dust suppressant potential of a biopolymer, wind tunnel testing allows for direct measurement of the wind erosion resistance of soil samples. In two successive phases, the study first tested multiple biopolymer concentrations and then several application rates to study the parameters' effects on the wind erosion and penetration resistance. The results of this study contributed to evaluating the dust suppressant potential of biopolymers and facilitated the selection of suitable biopolymers and application parameters for the final study phase.

Chapter 4 comprises **Article III: Large-Scale Field Trials** (p. 61ff.), which investigated the effectiveness of selected biopolymers in reducing airflow-induced dust emissions from exposed, undisturbed mine soils under field conditions. The field trials were conducted at the Inden open-cast lignite mine and started with the large-scale application of biopolymers using a conventional field sprayer. In the following weeks, the effectiveness of the treatments was repeatedly tested by subjecting trial plots to the airflow of an electric blower and measuring the generated dust emissions with an aerosol spectrometer. Visual inspections and penetrometer testing complemented the test programme, and the acquired data was analysed in the context of the meteorological data recorded by a nearby weather station.

Chapter 5 contains the **General Discussion, Implications and Recommendations** (p. 85ff.). It reviews the presented research, answers the *Main Research Question*, and discusses further criteria relevant to the dust suppressant potential of biopolymers. Finally, it articulates the implications of the thesis and makes recommendations for future work.

In the following chapters, this cumulative thesis presents the three published peer-reviewed academic journal articles. It should be noted that, except for the abstracts, the research articles have been included in their entirety and were only adjusted regarding their formatting for the sake of appearance and consistency. This results in minor, inevitable repetitions of content between the General Introduction and General Discussion chapters and the corresponding introduction and discussion sections of the research articles.

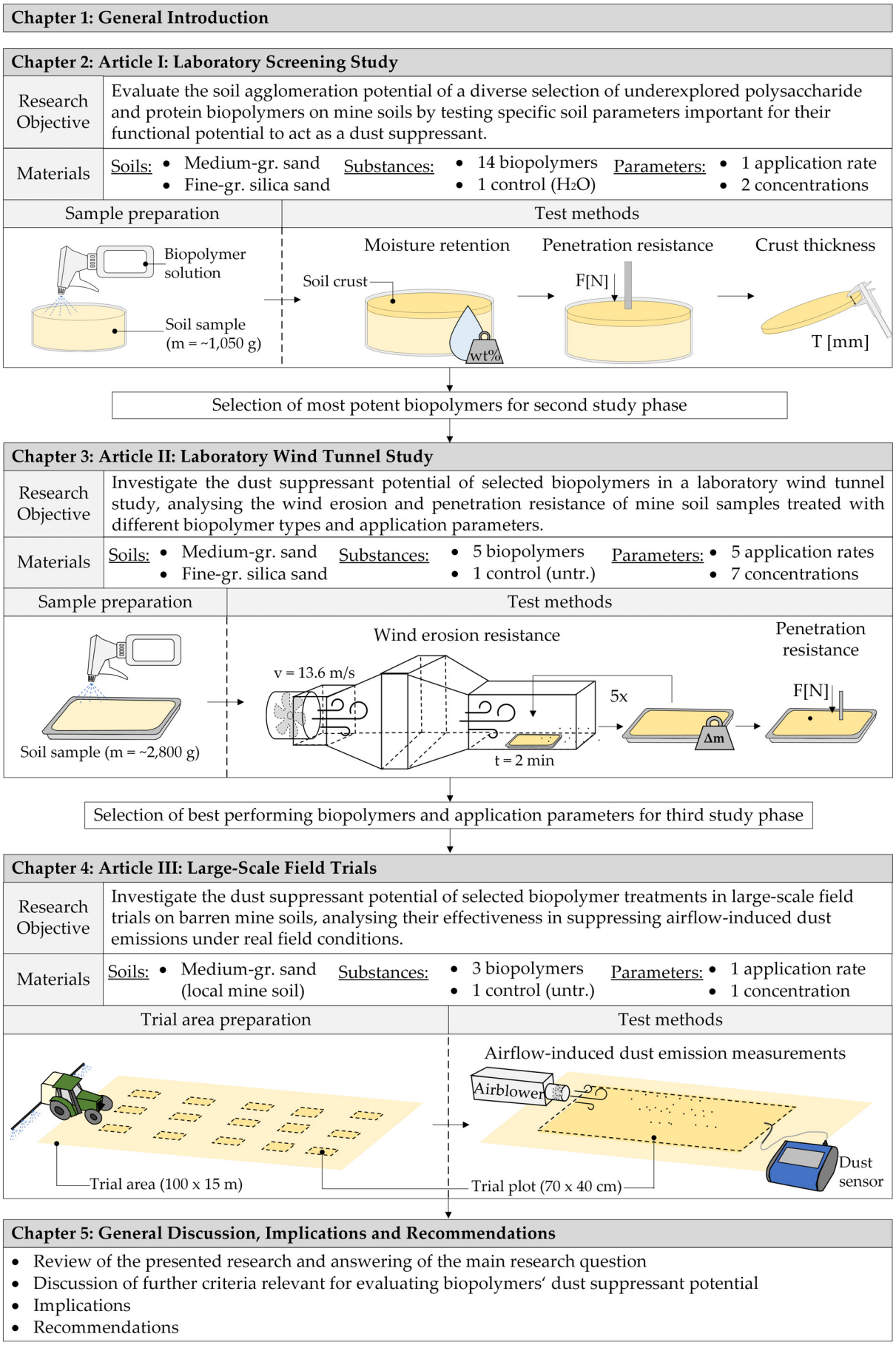


Figure 1.1: Thesis structure and graphical illustration of research methodology.

1.6 Significance

In the coming decades, dust emissions from active and legacy mines will pose a growing threat to workers, communities, and the environment as the footprint of mines and the frequency and severity of droughts and strong wind events increase. At the same time, water, the world's most common dust suppressant, is becoming increasingly scarce, while traditional suppressants are costly, non-renewable and can have adverse environmental impacts. While the need to control particulate matter and nuisance dust from mine soils is undisputed, mining companies are more challenged than ever to implement environmentally responsible operating practices. Therefore, there is a need for effective, inexpensive, and environmentally friendly dust suppressants to contribute to more environmentally benign dust control practices. Biopolymers potentially meet these needs, but their potential as dust suppressants remains under-explored.

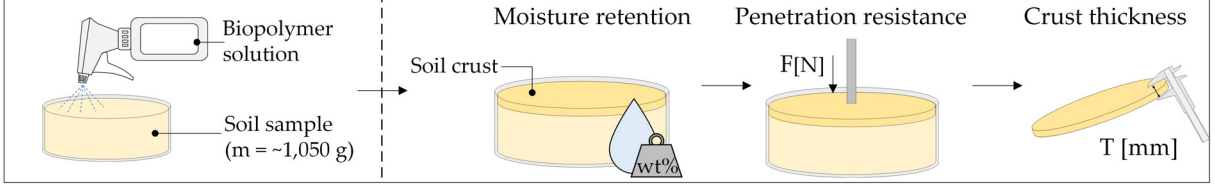
By investigating the potential of biopolymers as dust suppressants on barren mine soils, the results of this thesis will be significant for the evaluation and advancement of environmentally friendly dust control practices. This thesis will add to the existing body of knowledge by evaluating the functional potential of diverse biopolymers, which have been under-explored in this context, to agglomerate soil particles and improve soil wind erosion resistance. In addition, the research will reveal whether biopolymer treatments can effectively mitigate wind-induced dust emissions when applied on a large scale under real field conditions. By evaluating the potential of biopolymers as dust suppressants, this work will ultimately contribute towards advancing research into more environmentally friendly dust control practices and lowering the barriers to broader adoption by operators.

Chapter 2

Article I: Laboratory Screening Study

Evaluation of Protein and Polysaccharide Biopolymers as Dust Suppressants on Mine Soils: Laboratory Experiments

Chapter 2: Article I: Laboratory Screening Study	
Research Objective	Evaluate the soil agglomeration potential of a diverse selection of underexplored polysaccharide and protein biopolymers on mine soils by testing specific soil parameters important for their functional potential to act as a dust suppressant.
Materials	Soils: • Medium-gr. sand • Fine-gr. silica sand Substances: • 14 biopolymers • 1 control (H_2O) Parameters: • 1 application rate • 2 concentrations
Sample preparation	Test methods



Published: 11 January 2023
Authors: Johannes L. Sieger, Bernd G. Lottermoser, and Justus Freer
Keywords: dust suppressant; dust control; biopolymer; penetration resistance; crust strength; moisture retention; mine soil; protein; polysaccharide
Citation: Sieger, J.L., Lottermoser, B.G., Freer, J. Evaluation of protein and polysaccharide biopolymers as dust suppressants on mine soils: laboratory experiments. In: *Appl. Sci.* 13.2 (2023), p. 1010, Doi:10.3390/app13021010. Impact factor: 2.7.

2.1 Introduction

Fugitive dust emissions from industries such as mining pose a significant threat to the environment and the health of workers and surrounding communities [6, 32, 35, 173]. These emissions can cause respiratory diseases such as pneumoconiosis, asthma, or chronic obstructive pulmonary disease (COPD) [174], increase vehicle maintenance, and reduce occupational safety by limiting visibility [120, 175]. As climate change increases the frequency and severity of extreme weather events [176, 177], fugitive dust emissions are expected to rise in the coming decades. This is because prolonged heat waves lead to a faster depletion of soil moisture, increasing the susceptibility of soil particles to be suspended and become fugitive dust. Industries, such as mining, quarrying, construction, and agriculture, constitute the main sources of anthropogenic fugitive industrial (non-combustion) dust [178]. By their very nature, these domains encompass large, barren surfaces with a scarce vegetative cover exposed to frequent windblow and mechanical disturbances. Hence, these industries are challenged to reduce fugitive dust emissions at their sites.

Measures such as (vegetative) barriers or encapsulations reduce fugitive dust emissions but are unsuitable for protecting large, exposed areas or mitigating emissions caused by mechanical disturbance. In mining, the spray-on application of water is the oldest yet-established means for decreasing dust emissions, but its effect rapidly diminishes upon evaporation. Dust suppressants constitute an alternative solution for controlling dust emissions. They act by either agglomerating small particles, making them less prone to be suspended in the air, or are hygroscopic, absorbing moisture from the air to increase soil moisture [51]. However, many traditional dust suppressants, such as chloride salts or petroleum-based products, can adversely affect the environment [14] or are costly, resulting in the need for environmentally friendly and cost-effective alternatives.

Recently, the potential of biopolymers as environmentally friendly alternatives to traditional soil amendments has been increasingly investigated in the fields of soil stabilisation and dust control (e.g., [108, 110–112, 144]). Biopolymers are produced by living organisms, such as plants, microbes, and animals, are biodegradable, and can be classified into polysaccharides, proteins, and polynucleotides (e.g., deoxyribonucleic acid (DNA) and ribonucleic acid (RNA)) [179]. Soil stabilisation refers to the process of mixing soil amendments into the soil to enhance its engineering properties, while dust control refers to the spray-on application of dust suppressants [119]. Table A.1 (p.101) provides a comprehensive review of previous studies on different biopolymer types, and several reviews summarise the current research in the respective fields [69, 80, 81, 84, 85].

Based on previous studies (cf. Table A.1, p.101) and reviews, the current knowledge on biopolymers tested in soil stabilisation and dust control can be summarised as follows. (a) Most research focuses on polysaccharides, with xanthan and guar gum being the most studied, whereas only a few studies investigated proteins. Polynucleotides have not yet been investigated, likely because of their extremely high cost. (b) Many previous studies examined biopolymers from botanical sources native to tropical, arid, and partially temperate climates (e.g., guar, persian, acacia, and locust bean gum, or soybeans), hindering the ability of regional sourcing in regions with a continental climate, such as Central and Eastern Europe. (c) Some tested biopolymers are only dissolvable at high temperatures ($>80\,°C$) or in acetic or alkaline solutions. While such properties make these biopolymers more effective or resistant to degradation [129], such dissolution behaviour prevents large-scale field testing and site applications. (d) Most studies have focused on extensive testing with a single or a few biopolymers, with only a few comparative studies analysing multiple biopolymers.

Based on the current knowledge, the following research needs can be identified. (a) Research on underrepresented polysaccharides and especially proteins should be expanded to identify further biopolymers with potential as dust suppressants. (b) Research on biopolymers that can be sourced regionally in areas with continental climates should be increased to identify

alternative sources that may be procurable at a lower carbon footprint. (c) Emphasis should be on biopolymers that dissolve readily in water, enabling the conduct of large field tests under real site conditions.

This study aimed to investigate the dust suppression potential of selected polysaccharides and proteins (meeting the needs above) by performing laboratory experiments on local mine soils. Penetrometer tests were performed to measure the penetration resistance of the formed crusts, as it is an established and recommended indicator for evaluating potential dust suppressants [108, 112, 145, 180]. Moisture retention tests were conducted to evaluate the ability of biopolymer-treated soil to retain moisture, which is a further relevant indicator for analysing potential dust suppressants [112, 113, 145]. Crust thickness measurements were performed to assess the ability of different biopolymer types and concentrations to agglomerate particles and form crusts. The results of this research contribute to the evaluation of polysaccharide and protein biopolymers as environmentally friendly dust suppressants on large, barren surfaces.

2.2 Materials and Methods

2.2.1 Materials

Soils

Medium-grained sand. A 2 t bulk sample of medium-grained sand was provided by the Rheinische Baustoffwerke GmbH, which represents a sand and gravel operation located 16 km northeast of Aachen, Germany. The bulk sample is representative of overburden material that is extracted during lignite open-pit mining in the region. The material was air-dried at room temperature and homogenised by coning and quartering. Relevant soil properties (i.e., pH, specific gravity, and soil colour) and grain size distributions were determined at RWTH Aachen University. The particle-size distribution was determined according to DIN EN ISO 17892-4 (Table 2.1 and Figure 2.1) and based on the unified soil classification system (USCS); the material can be classified as medium-grained, poorly graded sand (SP). The sample's geochemistry was determined at ALS Geochemistry (Loughrea, Ireland), which performed whole-rock analysis by X-ray fluorescence spectroscopy (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) with four-acid digestion. Its mineralogy was established by semi-quantitative X-ray diffraction (XRD) using an X'Pert Pro (PANalytical) instrument with a data collector and an X'Pert High Score system equipped with a Co-LFF (Empyrian) tube and an automated divergence slit (Clausthal University of Technology, Germany). The sand primarily consists of quartz with plagioclase, ankerite, and rutile as accessories.

Fine-grained silica sand. A 1.5 t bulk sample of fine-grained silica sand was obtained from the Quarzwerke Frechen open-pit mine, which represents a silica sand operation located 8 km west of Cologne, Germany. The sand can be classified as medium- to fine-grained, poorly graded sand (SP) and its properties, as well as its geochemistry, are listed in Table 2.1. Semi-quantitative XRD showed that the sand primarily consists of quartz with ankerite and clinochlore as accessories.

Table 2.1: Physical and chemical properties of mine soils used by this study.

Parameter	Unit	Medium-Grained Sand	Fine-Grained Silica Sand	Test Method
Soil properties				
D_{60}	mm	0.75	0.24	DIN EN ISO 17892-4[181]
D_{50}	mm	0.63	0.22	DIN EN ISO 17892-4[181]
D_{30}	mm	0.43	0.18	DIN EN ISO 17892-4[181]
D_{10}	mm	0.28	0.14	DIN EN ISO 17892-4[181]
C_u	-	2.73	1.78	DIN EN ISO 17892-4[181]
C_c	-	0.91	0.95	DIN EN ISO 17892-4[181]
USCS classficiation	-	SP	SP	ASTM D-2487[182]
Specific gravity	g/cm³	2.59	2.63	DIN EN ISO 11508:2018-04[183]
pH value		7.53	6.48	DIN EN 15933:2012-11[184]
Soil colour	Munsell	9.7 YR 6.0/2.8	0.9 Y 7.1/1.3	
Geochemistry (oxides)				
SiO_2	wt%	94.58	98.65	
Al_2O_3	wt%	2.35	0.55	
K_2O	wt%	1.15	0.04	
Fe_2O_3	wt%	0.74	0.05	
Na_2O	wt%	0.22	0.01	
CaO	wt%	0.05	0.01	
MgO	wt%	0.10	0.01	
TiO_2	wt%	0.06	0.07	
P_2O_5	wt%	0.02	< 0.01	
MnO	wt%	0.01	< 0.01	

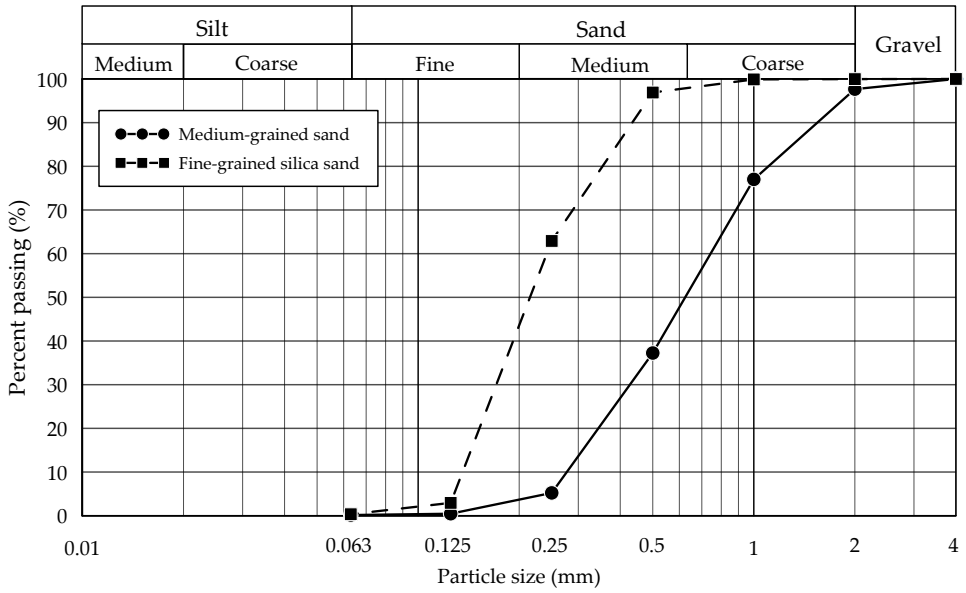


Figure 2.1: Particle-size distribution of medium-grained sand and fine-grained silica sand, determined according to DIN EN ISO 17892-4[181].

Biopolymers

Selection methodology. Fourteen different biopolymers (seven polysaccharides and seven proteins) were selected for this study (Table 2.2). The polysaccharides, xanthan gum (XG), and sodium lignosulphonate (NLS) were preselected because they have already been studied in detail by previous works [108, 109, 112], and hence experimental results can be compared. Three qualitative criteria were used to select biopolymers relevant to this study:

1. The biopolymer should be able to be sourced regionally within Central European countries where continental climate prevails.

2. The biopolymer should be commercially available at a relatively low cost compared to biopolymers investigated in previous studies, such as agar gum (avg. 18 USD/kg), alginates (avg. 12 USD/kg), carrageenan (avg. 10.5 USD/kg), chitosan (avg. 35 USD/kg), or pectin (avg. 15 USD/kg) [185–187].
3. The biopolymer should be readily soluble in water to enable large-scale field testing and potential industrial implementation. Such a requirement precludes biopolymers, whose dissolution would rely on either high temperature (e.g., agar or gellan gum) or acetic/alkaline solutions (e.g., chitosan or casein).

Selected biopolymers. Selected proteins and polysaccharides and relevant product information were obtained from the manufacturers (Table 2.2). Due to commercial sensitivity, the manufacturers did not allow the disclosure of their products' bulk prices. Thus, indicative bulk prices obtained from other articles are provided below. The polysaccharides used include carboxymethyl cellulose (CMC, 1.4 USD/kg), NLS (0.2–0.5 USD/kg), XG (2.0–3.0 USD/kg), and four different modified starches (corn, pea, potato, and wheat, typically <1.0 USD/kg in bulk) [75, 78, 85, 188, 189]. The chosen proteins comprise the plant-based fava bean protein concentrate (FBPC, 1.4–2.5 USD/kg) and wheat protein (WP, 1.4–2.5 USD/kg)) and the animal-based proteins hen egg albumen (HEA, 6.0–8.0 €/kg), porcine haemoglobin protein (HG, 0.7–1.0 USD/kg), porcine plasma protein (PP, 3.5–4.5 USD/kg), technical gelatine (TG, 4–6 USD/kg), and whey protein concentrate (WPC, 5.5 USD/kg) [190, 191]. While technical gelatine does not strictly meet criterion (3.), it was still selected because the temperature required to dissolve it (40 °C) is still modest.

Table 2.2: Biopolymers investigated by this study and their product data.

Biopolymer	**Product Name**	**Specification**	**Manufacturer**	**Appearance**	**Moisture (wt%)**
Polysaccharides					
Carboxymethyl cellulose (CMC)	DTK NV CMC	Technical grade, low viscosity	Mikro-Technik-CMC	Light-yellowish granules	8.6 [a]
Corn starch (CS)	C-Gel Instant	Pregelatinised	Cargill GmbH	White powder	5.8 [b]
Sodium lignosul -phonate (NLS)	N18	Cold-water soluble	Otto Dille GmbH	Brown powder	8.6 [a]
Pea starch (PES)	Emcol EST (F11025)	Pregelatinised	Emsland Group	Off-white powder	10.4 [b]
Potato starch (POS)	KMC 18-09	Pregelatinised (acetylated)	KMC Germany	White powder	9.4 [b]
Wheat starch (WS)	Tigel	Pregelatinised	Krörner Stärke	White powder	6.3 [b]
Xanthan gum (XG)	XG TGRD	Technical grade, readily dispersible	Jungbunzlauer	White, free-flowing powder	5.1 [a]
Proteins					
Fava bean protein concentrate (FBPC)	ABPK 65%	Enzyme activated	Aloja-Starkelsen	Creamy light-yellow powder	8.8 [d]
Hen egg albumen (HEA)	Hen egg albumen	Cold-water soluble	Ovopol Sp. z. o.o.	Yellowish powder	7.0 [a]
Haemoglobin protein (HG)	HG 92P	Haemoglobin powder, porcine protein	Sonac	Dark red powder	6.6 [c]
Plasma protein (PP)	PP 70P	Plasma powder, porcine protein	Sonac	Cream-white powder	7.5 [c]
Technical gelatine (TG)	TG 330	Water soluble at ≥40°C	Hellmann GmbH	Yellowish, free-flowing granules	13.0 [a]
Wheat protein (WP)	Glusol	Degraded, without viscoelastic properties	Kröner Stärke	Yellowish powder	6.0 [d]
Whey protein concentrate (WPC)	Instant WPC 80	From fresh cheese whey	Lactoland GmbH	White to pale yellow powder	6.2 [d]

Note. [a] = data provided by manufacturer, [b] = measured in accordance with DIN EN ISO 1666:1997 [192], [c] = measured in accordance with ISO 6496:1999 [193], [d] = measured in accordance with AOAC 930.15 [194]

2.2.2 Laboratory Experiments

All experiments were conducted on two substrates (medium-grained sand and fine-grained silica sand), using replicates (3x) and control (distilled water) samples and 14 different biopolymers at a fixed application rate and two different concentrations. The fixed application rate was set at 1.6 L/m² (20.3 mL per sample), and the biopolymer concentrations were chosen as 1.0 and 2.0 wt%. These values were chosen as they are within the range recommended by the literature and have been used in previous studies [14, 108, 110, 112, 114]. XG was applied at only 0.25 and 0.50 wt% because higher concentrations yield too viscous solutions for spraying. Each sample was subject to (a) moisture retention tests, (b) penetrometer testing, and (c) crust weight and thickness measurements.

Sample preparation

Overall, 174 substrate samples were prepared and tested. Air-dried soil was placed into acryl glass cylinder moulds (127 mm diameter, 50 mm height, 126.7 cm² sample surface area). Samples were gently shaken to ensure slight and uniform compaction. Subsequently, sample surfaces were levelled with a ruler so that they were flush with the edge of the acryl glass cups. The resulting medium-grained sand samples weighed, on average, 1027 g ($SD = 40.6$ g) and the fine-grained silica sand samples 1109 g ($SD = 38.6$ g) (Figure 2.2a).

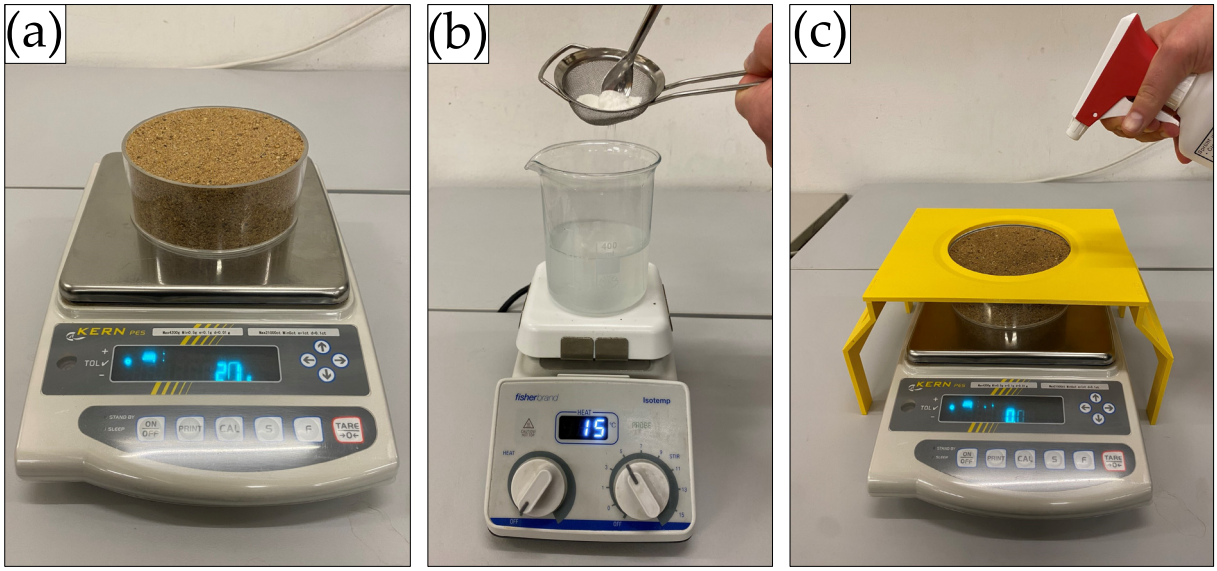


Figure 2.2: (**a**) Weighing of dry sample, (**b**) preparation of biopolymer solution, (**c**) gravimetric spray-on application of biopolymer solution with splash guard.

The calculation of the biopolymer mass required for the preparation of the individual solutions also accounted for the biopolymers' respective dry mass (Table 2.2). The biopolymer powders were dissolved at room temperature in distilled water at the specified concentrations for 10 min using a magnetic stirrer until fully dissolved (Figure 2.2b). To avoid clumping of the biopolymers, powders were slowly added to the distilled water through a sieve. The TG solution required preparation in 40 °C warm water.

The biopolymer solutions were sprayed onto the samples using a trigger sprayer with a nozzle suitable for viscous solutions (Ballistol hand atomizer, standard nozzle, Figure 2.2c). Uniform and accurate spray-on application was achieved by placing the untreated samples on a precision scale (Kern PES 4200-2M, 0.001 g resolution) and spraying the solution until the required application rate was achieved. Changes in solution density caused by the addition of biopolymer were

considered negligible, so a fixed solution density of 1.0 g/mLwas assumed for converting the required volumetric application rate (20.3 mL) to the gravimetric application rate (20.3 g). A 3D-printed splash guard was used to prevent the biopolymer solution from inadvertently touching the scale's weighing plate and thus distorting the scale readings (Figure 2.2c). After achieving the required application rate, the edges of the cylinder moulds were wiped dry. In the sample preparation process, the following weight measurements were recorded: weight of the empty sample moulds, dry sample weight, and total sample weight after biopolymer application.

Moisture Retention Tests

The ability of a biopolymer to enhance the soil moisture retention capacity is one determinant of its potential as a dust suppressant. Soil with increased moisture retention capacity can bind water over longer periods and slow the evaporation effect [169]. Moisture makes soil particles heavier and enhances the interparticle binding force [112], causing it to be less susceptible to being suspended in the atmosphere by erosive forces.

For the moisture retention tests performed in this study, the weights of the samples were recorded before and immediately after the biopolymer application. The treated samples were then cured in the laboratory (RWTH Aachen, spring) for four days (96 h) at ambient temperature $21 \pm 1\,°C$ and humidity (45 ± 2.5 wt%), their weights were recorded every 24 h ($t = 0, 24, 48, 72$ and 96 h post application). The moisture retention, ω (wt%), was calculated as the proportion of the initial moisture applied at $t = 0$ h that was retained in the sample at $t = 96$ h and was calculated according to Equation 2.1:

$$\omega = \frac{(m_1 - m_{dry})}{(m_0 - m_{dry})} \times 100 \tag{2.1}$$

where m_1 denotes the sample weight after 96 h of curing (g), m_0 is the sample weight after application of the biopolymer solution (g), and m_{dry} represents the dry sample weight prior to the application of the biopolymer solution (g).

Penetrometer Tests

Penetrometer tests allow measuring the maximum penetration resistance of soil crusts under controlled conditions. This analytical approach has already been applied by numerous studies investigating dust control agents [108–113, 116, 117]. A penetrometer is a stationary loading machine mounted with a pin to penetrate the soil crust at a set penetration angle and rate, continuously recording the penetration force and depth. Ding et al. [108] concluded that penetration resistance is a good indicator for predicting the dust control performance of a biopolymer and is even better suited than the UCS. In addition, Toufigh and Ghassemi [112] reported a strong correlation between results from the penetrometer and wind tunnel tests. Thus, penetrometer tests are a recommended and established method for evaluating potential dust suppressants.

The penetrometer tests were performed with a 6.4 mm (1/4 inch) diameter flat-ended cylindrical penetrometer pin that was mounted to a Wille UL 60/100 loading machine equipped with a 0.001 N resolution calibrated load cell (Institute of Geomechanics and Underground Technology, RWTH Aachen University, Germany). One penetration test was performed in the centre of each sample, pursuing a 4 mm penetration depth at an advance rate of 2 mm/min, a data logging interval of 5 Hz, and a fixed penetration angle of 90 ° (Figure 2.3). Since the penetrometer records penetration resistance alongside the penetration depth, the crusts' modulus of elasticity (M_e, $kN \times m^{-1}$) could be calculated by dividing the maximum penetration resistance (N) by the penetration depth reached at the moment of rupture.

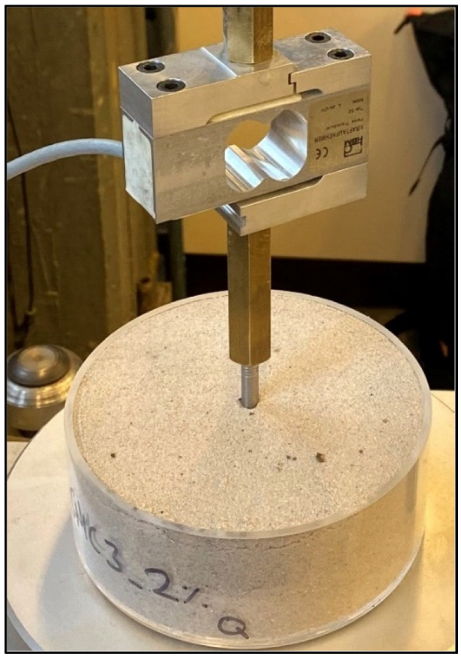


Figure 2.3: Penetrometer testing of fine-grained silica sand sample.

Crust Thickness Measurements

After penetration testing, the weight and thickness of every crust were measured. Therefore, crusts were carefully removed from the sample mould using a small spatula (Figure 2.4a,b). Depending on crust strength and brittleness, crusts could either be recovered in one piece, broke down into multiple recoverable pieces, or were very thin, weak, and brittle and, thus, barely recoverable. The samples were weighed again after the removal of the crusts, which allowed the calculation of the crust weight (Figure 2.4c). Together with the weight recordings and known dimensions of every sample mould, each crust's average density and thickness were established.

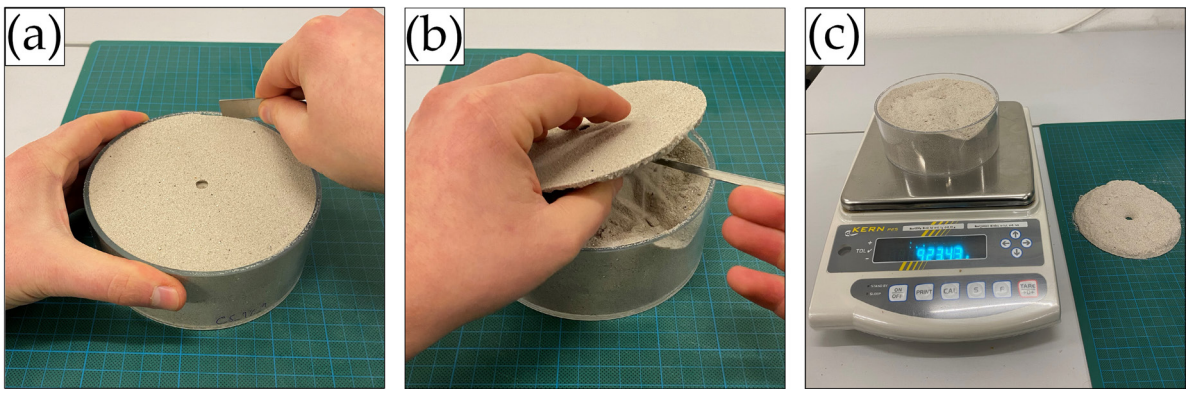


Figure 2.4: Process of removing the crust from the sample. (**a**) Loosening of the crust with a spatula from the mould rim, (**b**) removal of the crust with a spatula, (**c**) weighing of the sample without the crust.

Statistical Analysis

Two-way analysis of variance (ANOVA) with $\alpha = .05$ was performed to analyse whether biopolymer type and concentration had a significant effect on the measured parameters. Two-way ANOVA is a statistical method used to analyse whether two individual independent variables (i.e., biopolymer type and concentration), as well as their interaction (biopolymer type $\times$ concentration), have

a significant effect on one dependent variable (i.e., moisture retention, penetration resistance, and crust thickness) or not. If the resulting p-value is $< .05$, it can be concluded that the corresponding independent variable or their interaction has a significant effect on the analysed dependent variable. Separate statistical analyses were performed for the polysaccharides and proteins, medium-grained sand, and fine-grained silica sand. As recommended by the literature, any percentage data (moisture retention tests) were subject to square-root data transformation before performing the two-way ANOVA [195].

2.3 Results

2.3.1 Moisture Retention Tests

Medium-Grained Sand

Results of the moisture retention tests are shown in Figure 2.5 (exact values are appended in Table A.2, p. 102). Four days (96 h) after treatment, the control sample, which was treated with water, contained 6.9 %($SD = 1.2$) of the initially applied 20.3 g water. In the following, results of the polysaccharide and protein applications on the medium-grained sand are presented and compared.

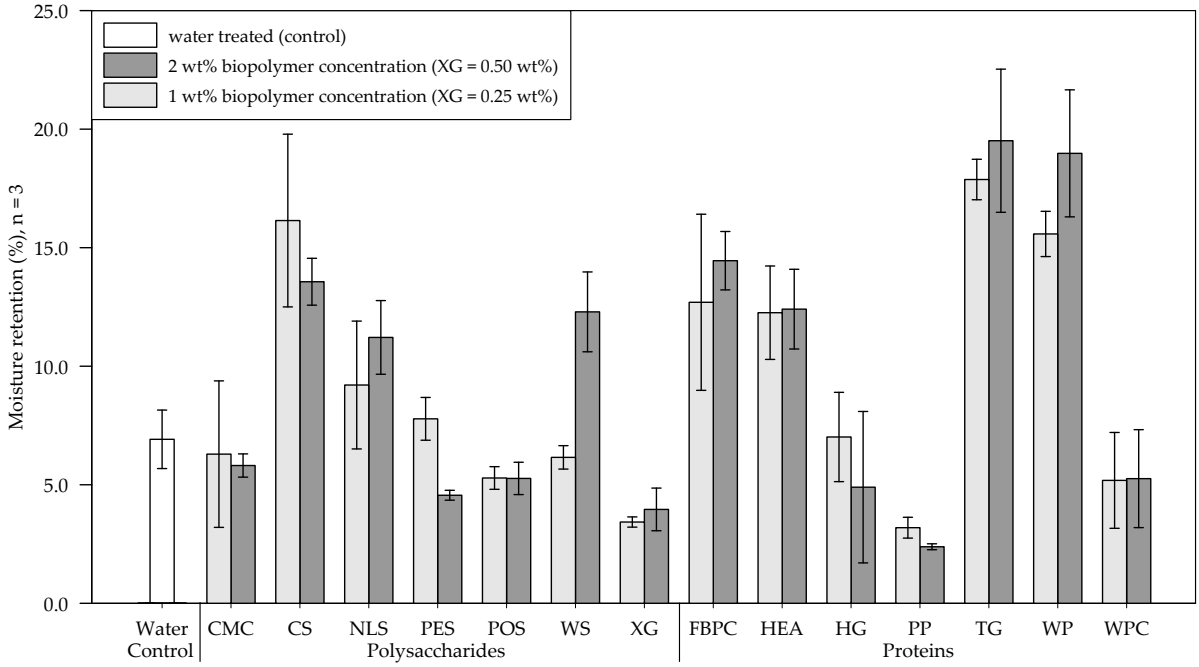


Figure 2.5: Mean moisture retention of medium-grained sand samples 4 days (96 h) after treatment at 1.6 L/m² and biopolymer concentrations of 1 and 2 wt% (XG = 0.25 and 0.50 wt%). Biopolymers are grouped into polysaccharides and proteins with water as control. Tests were performed in triplicates ($n = 3$), and error bars indicate the standard deviation (SD). Note. The exact values of experimental results are appended in Table A.2, p. 102.

Polysaccharides. Compared to the control, the 1 wt% (XG = 0.25 wt%) treatments either increased or decreased the samples' moisture retention. A slight reduction in moisture retention was observed for samples treated with CMC, POS, WS, and XG, whereas it increased for samples treated with CS, NLS, and PES. Relative to the 1 wt% treatment, the application of 2 wt% resulted in the samples' moisture retention either decreasing, increasing, or changing negligibly. It decreased

slightly for CMC and CS and significantly for PES, while no change was observed for POS. By contrast, it moderately increased for NLS and XG and even doubled for WS-amended samples.

Proteins. Protein applications at 1 wt% concentration reduced the moisture retention for samples amended with PP and WPC relative to the control group, while a negligible effect was observed for HG. Doubling the concentration decreased moisture retention for HG- and PP-treated samples, increased it for FBPC-, TG-, and WP-amended samples and had a negligible effect on applications with HEA and WP.

Comparison of polysaccharide and protein treatments. At the 1 wt% concentration, the polysaccharide-treated samples had, on average, higher moisture retention than the protein-amended samples. Doubling the concentration resulted in a slight increase in the average moisture retention of polysaccharide and protein-treated substrate. A direct comparison of the polysaccharide and protein amendments that resulted in the highest moisture retention shows that the material treated with proteins achieved higher moisture retention regardless of the concentration tested.

Statistical analysis. Results of the two-way ANOVA (Table 2.3) show that the types of polysaccharide ($p < .001$) and protein ($p < .001$) have a significant effect on moisture retention, whereby no general trend could be identified as to whether the treatments increase or decrease moisture retention. Doubling the concentration has no significant effect on moisture retention among polysaccharide- ($p = .596$) and protein-amended samples ($p = .470$), and there is no general trend, whether doubling the concentration results in the moisture retention to increase or decrease.

Table 2.3: Results of two-way ANOVA ($\alpha = .05$) of moisture retention. Percentage values were transformed via square root transformation prior to performing two-way ANOVA.

Group	Factor	SS	df	MS	F	p
Medium-Grained Sand						
Polysaccharides	Type	0.01297	6	0.00216	20.578	<.001
	Concentration	0.00003	1	0.00003	0.288	0.596
	Interaction	0.00219	6	0.00036	3.48	0.011
	Error	0.00294	28	0.00011	0	
Proteins	Type	0.03497	6	0.00583	34.945	<.001
	Concentration	0.00009	1	0.00009	0.538	0.469
	Interaction	0.00075	6	0.00013	0.752	0.613
	Error	0.00467	28	0.00017		
Fine-Grained Silica Sand						
Polysaccharides	Type	0.00241	6	0.0004	20.551	<.001
	Concentration	0.00008	1	0.00008	4.136	0.052
	Interaction	0.00089	6	0.00015	7.598	<.001
	Error	0.00055	28	0.00002		
Proteins	Type	0.04336	6	0.00723	197.48	<.001
	Concentration	0.00056	1	0.00056	15.193	<.001
	Interaction	0.00103	6	0.00017	4.691	0.02
	Error	0.00102	28	0.00004		

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

Conclusions. On medium-grained sand, the type of biopolymers has a significant effect on the samples' moisture retention, whereby some biopolymers significantly increased moisture retention. In contrast, others have a negligible effect or even decrease moisture retention relative to the

control sample treated with water. The biopolymer's concentration does not have a significant effect on the moisture retention of the treated samples.

Fine-Grained Silica Sand

Results of moisture retention tests are depicted in Figure 2.6 (exact values are appended in Table A.2, p. 102). Four days (96 h) after treatment, the control sample, which was treated with water, contained 2.5 % ($SD = 0.7$) of the initially applied 20.3 g of water. In the following, results of the polysaccharide and protein applications to the fine-grained silica sand are presented and compared.

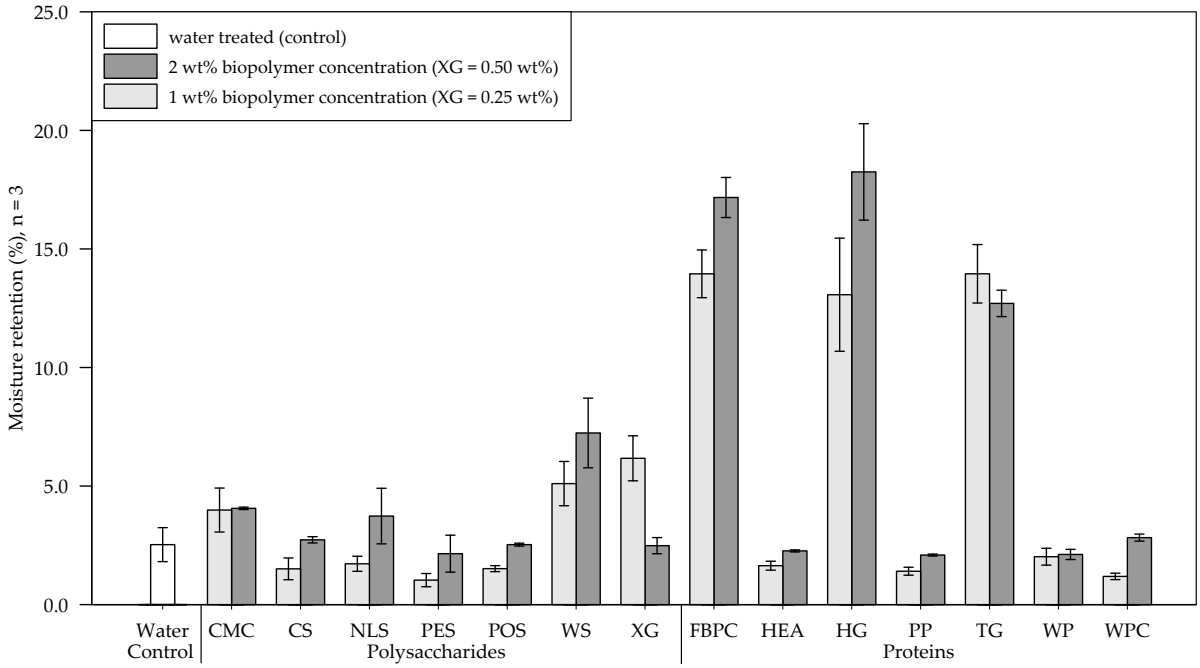


Figure 2.6: Mean moisture retention of fine-grained silica sand samples 4 days (96 h) after treatment at 1.6 L/m² and biopolymer concentrations of 1 and 2 wt% (XG = 0.25 and 0.50 wt%). Biopolymers are grouped into polysaccharides and proteins with water as control. Tests were performed in triplicates ($n = 3$), and error bars indicate the standard deviation (SD). Note. The exact values of experimental results are appended in Table A.2, p. 102.

Polysaccharides. In relation to the control sample, a 1 wt% (XG = 0.25 wt%) biopolymer treatment decreased the moisture retention of substrates treated with CS, NLS, PES, and POS, whereas an increase was observed for samples amended with CMC, WS, and XG. Increasing the concentration to 2 wt% (XG = 0.50 wt%) significantly decreased the moisture retention of XG-treated samples, and CMC had a negligible effect. By contrast, significant increases in moisture retention were observed for samples subject to applications with CS, NLS, PES, POS, and WS.

Proteins. Biopolymer applications at 1 wt% reduced the moisture retention for samples amended with HEA, PP, WP, and WPC compared to the control group. At the same time, significant increases were observed for FBPC, HG, and TG, respectively. When the concentration was doubled to 2 wt%, the moisture retention of the TG-treated silica sand decreased slightly, while the remaining proteins increased moisture retention.

Comparison of polysaccharide and protein treatments. At both tested biopolymer concentrations, the protein-treated samples, on average, showed significantly higher moisture retention than the polysaccharide-amended soils. A comparison of the polysaccharide- and protein-treated silica

sand samples that achieved the highest moisture retention shows that the proteins performed better regardless of the tested concentration.

Statistical analysis. Results of the two-way ANOVA (Table 2.3) show that the types of polysaccharide ($p < .001$) and protein ($p < .001$) have a significant effect on moisture retention, with some biopolymers having a negligible effect, others decreasing moisture retention, and some resulting in the retention rate increasing significantly. Doubling the biopolymer concentration slightly or even considerably increases moisture retention for all biopolymers except XG and TG. A significant effect of concentration on moisture retention is only indicated for the tested proteins ($p < .001$) and not for the polysaccharides ($p = .052$).

Conclusions. On fine-grained silica sand, the biopolymer type has a significant effect on the samples' moisture retention, with some biopolymers increasing moisture retention, whereas others only result in minor changes or even decrease it relative to the control sample treated with water. Moisture retention of the treated silica sand is significantly influenced by the protein concentration.

2.3.2 Penetrometer Tests

Medium-Grained Sand

On medium-grained sand, all tested biopolymer applications formed crusts, and the results of the penetrometer tests are shown in Figure 2.7 (exact penetration resistance values and the results of the modulus of elasticity calculations are appended in Table A.3 (p. 103) and Table A.4 (p. 104), respectively). Four days after treatment, the control group, treated with water, endured a maximum penetration resistance of 1.5 N ($SD = 0.1$).

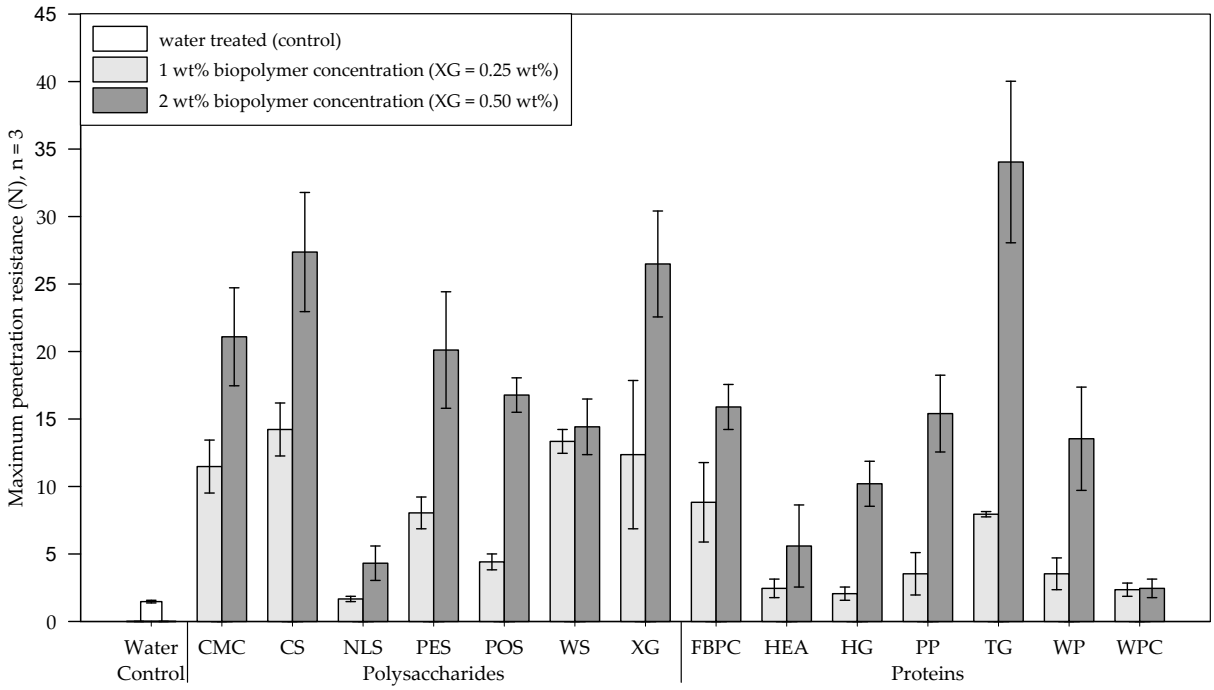


Figure 2.7: Mean maximum penetration resistance of crusts from medium-grained sand samples measured by penetrometer tests. Biopolymers are grouped into polysaccharides and proteins with water as control. Tests were performed in triplicates ($n = 3$), with error bars indicating the standard deviation (SD). Note. The exact values of experimental results are appended in Table A.3, p. 103.

Polysaccharides. Compared to the control, 1 wt% (XG = 0.25 wt%) treatments with NLS had a negligible effect on the penetration resistance. By contrast, treatments with POS resulted in a slight increase in penetration resistance, whereas the remainder of the tested polysaccharide applications showed significant increases. When the concentration was increased to 2 wt% (XG = 0.50 wt%), the penetration resistance of substrate amended with WS slightly increased, while all other tested polysaccharides showed significant increases, with CS and XG achieving the highest penetration resistances among all tested biopolymers.

Proteins. The application at a concentration of 1 wt% slightly increased the penetration resistance of sand treated with HEA, HG, PP, WP, and WPC compared to the control group treated with water. By contrast, substrates amended with FBPC and TG exhibited significantly higher penetration resistances. Relative to 1 wt%, the 2 wt% protein applications increased the maximum penetration resistance of all treated samples, except for WPC. Applications with HG, PP, and TG displayed the greatest increases in penetration resistance.

Comparison of polysaccharide and protein treatments. When biopolymers were applied at concentrations of 1 wt% (XG = 0.25 wt%), polysaccharide-induced crusts were, on average, more than twice as resistant to penetration than protein-induced crusts. Doubling the concentration to 2 wt% (XG = 0.50 wt%) resulted in a disproportionate increase in the penetration resistance of the protein-induced crusts compared to the polysaccharide-induced crusts, with the polysaccharide treatments still achieving higher absolute penetration resistances.

Statistical analysis. Results of the two-way ANOVA (Table 2.4) show that the types of polysaccharide and protein have a significant effect on the penetration resistance ($p < .001$), with some biopolymer treatments achieving significantly higher penetration resistances than others. Among the proteins and polysaccharides, the concentration has a significant effect ($p < .001$) on the penetration resistance, whereby higher concentrations mostly enhanced the penetration resistance significantly.

Table 2.4: Results of two-way ANOVA ($\alpha = .05$) of penetration resistance measured by penetrometer.

Group	**Factor**	**SS**	**df**	**MS**	**F**	***p***
Medium-Grained Sand						
Polysaccharides	Type	1277.93	6	212.99	17.57	< .001
	Concentration	908.3	1	908.3	74.93	< .001
	Interaction	250.04	6	41.67	3.44	0.011
	Error	339.46	28	12.12		
Proteins	Type	1386.02	6	231	24.74	< .001
	Concentration	952.47	1	952.47	101.99	< .001
	Interaction	623.11	6	103.85	11.12	< .001
	Error	261.49	28	9.34		
Fine-Grained Silica Sand						
Polysaccharides	Type	582.82	6	97.14	4.91	< .001
	Concentration	108.78	1	108.78	5.5	0.026
	Interaction	227.89	6	37.98	1.92	0.113
	Error	554.29	28	19.8		
Proteins	Type	1753.52	6	292.25	21.93	< .001
	Concentration	798.95	1	798.95	59.95	< .001
	Interaction	298.17	6	49.7	3.73	0.007
	Error	373.13	28	13.33		

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

Conclusions. On medium-grained sand, the type of biopolymer and concentration have a significant effect on the resulting penetration resistance of the cured crusts. Some biopolymers enhanced the penetration resistance only slightly or negligibly, while others had a considerable effect. For most biopolymers, doubling the concentration increased the achieved penetration resistance considerably.

Fine-Grained Silica Sand

Results of the penetrometer tests performed on fine-grained silica sand samples are shown in Figure 2.8 (exact values are appended in Table A.3, p. 103). Four days after treatment, the water-treated control group had a maximum penetration resistance of 1.7 N ($SD = 0.2$).

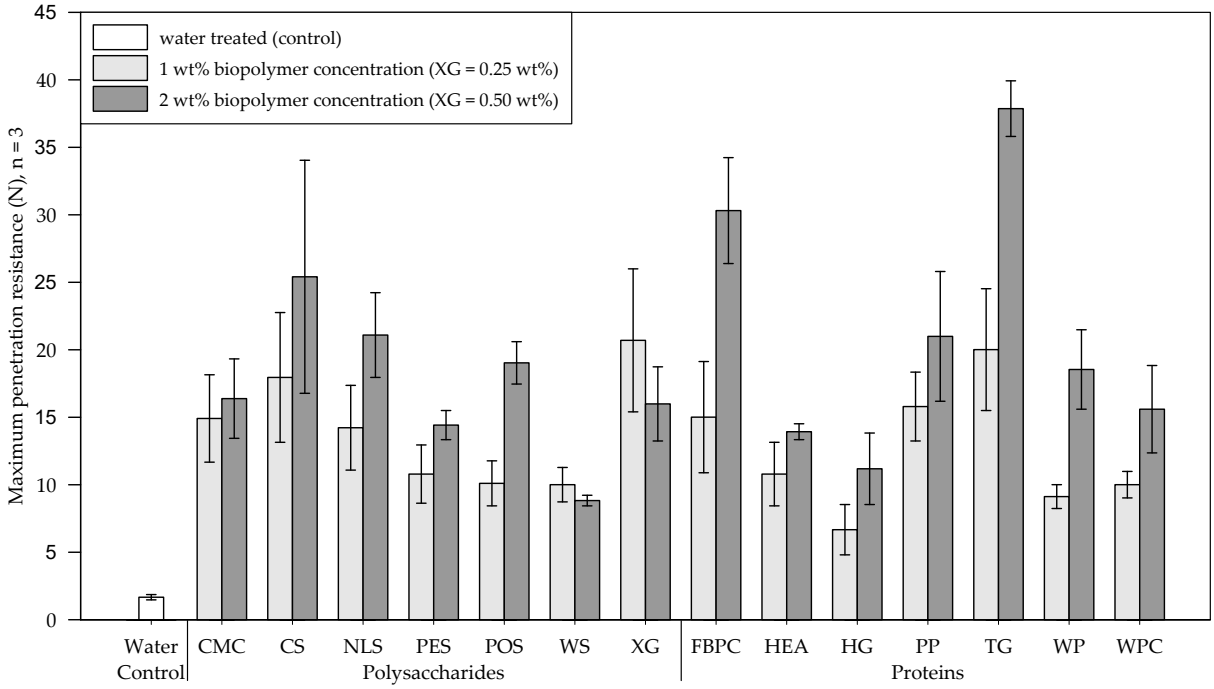


Figure 2.8: Mean maximum penetration resistance of crusts from fine-grained silica sand samples measured by penetrometer tests. Biopolymers are grouped into polysaccharides and proteins with water as control. Tests were performed in triplicates ($n = 3$), with error bars indicating the standard deviation (SD). Note. The exact values of experimental results are appended in Table A.3, p. 103.

Polysaccharides. At biopolymer concentrations of 1 wt% (XG = 0.25 wt%), all tested polysaccharide types formed crusts with considerably enhanced penetration resistances compared to the control group treated with water. Increasing the concentration significantly enhanced the penetration resistance of all tested polysaccharides, except for WS and XG, whose penetration resistance decreased.

Proteins. Relative to the control group treated with water, all protein admixtures applied at 1 wt% concentration formed crusts with significantly increased penetration resistances. Compared to treatments at 1 wt% concentration, applications at 2 wt% resulted in the penetration resistance of all tested proteins increasing significantly, with FBPC, TG, and WP experiencing the most significant increases.

Comparison of polysaccharide and protein treatments. For amendments at 1 wt% concentration, polysaccharide-induced crusts, on average, endured slightly higher penetration resistances than protein-induced crusts. While doubling the concentration significantly increased the penetration

resistance of almost all samples, the penetration resistance of protein-induced crusts displayed a disproportionate increase relative to polysaccharide crusts. At the higher biopolymer concentration, the protein-treated substrates, on average, showed higher penetration resistances than the polysaccharides.

Statistical analysis. Results of the two-way ANOVA (Table 2.4) show that the types of polysaccharide ($p < .001$) and protein ($p < .001$) have a significant effect on the penetration resistance, with some biopolymers forming significantly stronger crusts than others. The concentration also has a significant effect on the penetration resistance (polysaccharide: $p = .026$, proteins: $p < .001$), whereby doubling the concentration significantly increased the penetration resistance of most tested amendments.

Conclusions. On fine-grained silica sand, all biopolymers produced crusts with significantly increased penetration resistances relative to the control group, with the biopolymer type having a significant effect on the resulting penetration resistance. The effect of doubling the concentration strongly depends on the biopolymer type, whereby most biopolymer treatments exhibited significant increases.

2.3.3 Crust Thickness Measurements

Medium-Grained Sand

The results of the crust thickness measurements are shown in Figure 2.9 (exact values are appended in Table A.5, p. 105). Figure 2.10 and Figure 2.11 show exemplary pictures of upside-down-facing crusts formed by the tested biopolymer amendments (visual classification appended in Table A.6, p. 106). While the control group, treated with water, formed no recoverable crust, all tested biopolymers formed crusts of varying thicknesses.

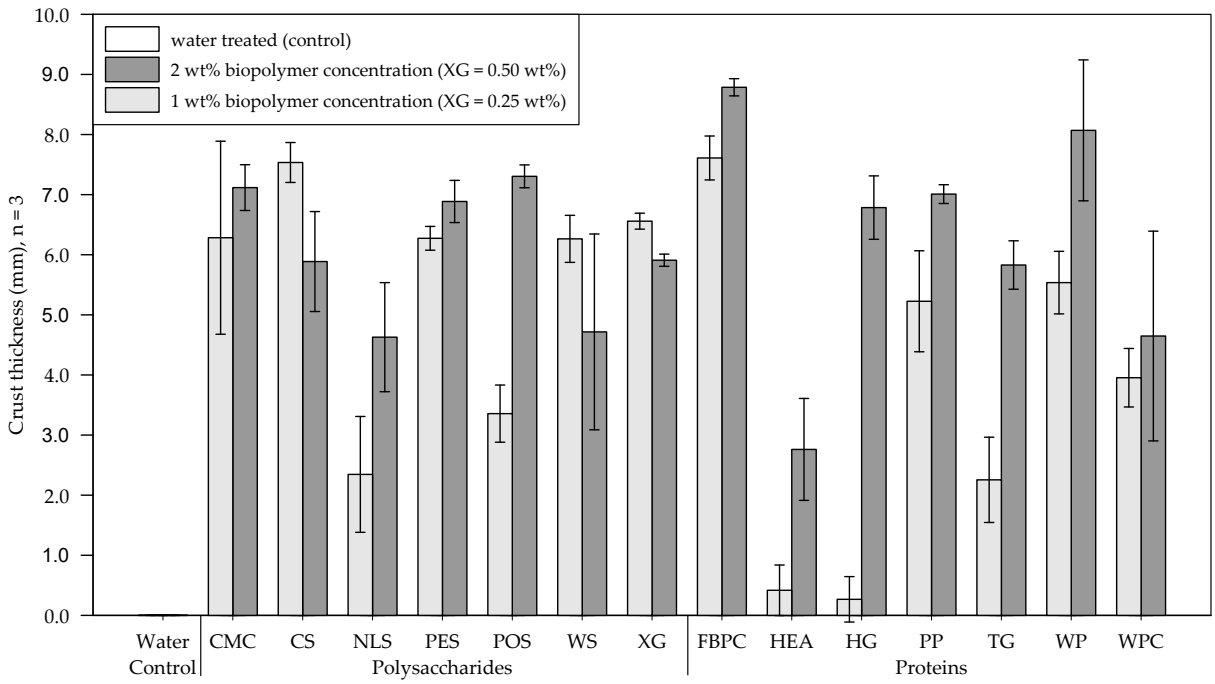


Figure 2.9: Mean thickness of crust formed on medium-grained sand samples. Biopolymers are grouped into polysaccharides and proteins with water as control. Tests were performed with three replicas ($n = 3$), with error bars indicating the standard deviation (SD). Note. The exact values of experimental results are appended in Table A.5, p. 105.

Polysaccharides. Treatments at 1 wt% (XG = 0.25 wt%) produced crusts ranging from 2 to 7.2 mm in thickness. While amendments with NLS and POS formed relatively thin to medium-thick crusts, the remaining polysaccharide applications yielded thick crusts on medium-grained sand. Compared to the 1 wt% treatment, doubling the concentration decreased the crust thickness for substrate treated with XG, CS, and WS, while crusts resulting from amendments with CMC and PES displayed a slight, and NLS and POS a significant, increase in thickness, respectively.

Proteins. Protein applications at 1 wt% concentration produced crusts of varying thickness. While treatments with HEA and HG formed fragile, brittle, and barely recoverable crusts, TG already formed slightly thicker crusts. Thick crusts formed on medium-grained sand amended with PP, WP, WPC, and FBPC, with the latter resulting in the thickest crusts of all biopolymers tested at 1 wt%. At the higher tested concentration, the crust thicknesses of all treatments increased, whereby HEA, TG, and HG displayed the most significant increases.

Comparison of polysaccharide and protein treatments. At treatments with 1 wt% (XG = 0.25 wt%) biopolymer concentration, medium-grained sand amended with polysaccharides, on average, formed slightly thicker crusts than applications with proteins. Doubling the concentration to 2 wt% (XG = 0.50 wt%) resulted in the thickness of polysaccharide-induced crusts to increase slightly, while protein-induced crusts displayed significant increases.

Statistical analysis. Results of the two-way ANOVA (Table 2.5) show that the types of polysaccharide ($p < .001$) and protein ($p < .001$) have a significant effect on the crust thickness, with some biopolymers forming only very thin crusts and others thick crusts. Increasing the concentration only had a significant effect on the crust thickness of protein amendments ($p < .001$), whereby increasing the concentration caused the crust thickness of all protein-treated samples to increase.

Table 2.5: Results of two-way ANOVA ($\alpha = .05$) of mean crust thickness.

BP Type	Factor	SS	df	MS	F	*p*
Medium-Grained Sand						
Polysaccharides	Type	48.6	6	8.1	8.86	< .001
	Concentration	3.15	1	3.15	3.44	0.074
	Interaction	37.96	6	6.33	6.92	< .001
	Error	25.61	28	0.91	0	
Proteins	Type	188.1	6	31.35	38.42	< .001
	Concentration	77.67	1	77.67	95.18	< .001
	Interaction	33.83	6	5.64	6.91	< .001
	Error	22.85	28	0.82	0	
Fine-Grained Silica Sand						
Polysaccharides	Type	636.09	6	106.01	84.27	< .001
	Concentration	1.47	1	1.47	1.17	0.288
	Interaction	49.2	6	8.20	6.52	< .001
	Error	35.23	28	1.26	0	
Proteins	Type	75.25	6	12.54	8.44	< .001
	Concentration	5.08	1	5.08	3.42	0.075
	Interaction	15.02	6	2.50	1.69	0.161
	Error	41.6	28	1.49	0	

Conclusions. On medium-grained sand, all biopolymer treatments formed crusts, with the resulting crust thickness varying significantly among the biopolymers tested. For most polysaccharides, doubling the concentration only slightly increased the crust thickness, whereas most protein treatments exhibited significant increases in crust thickness.

Figure 2.10: Examples of polysaccharide-induced crusts recovered from the samples (cf. Table A.6, p. 106).

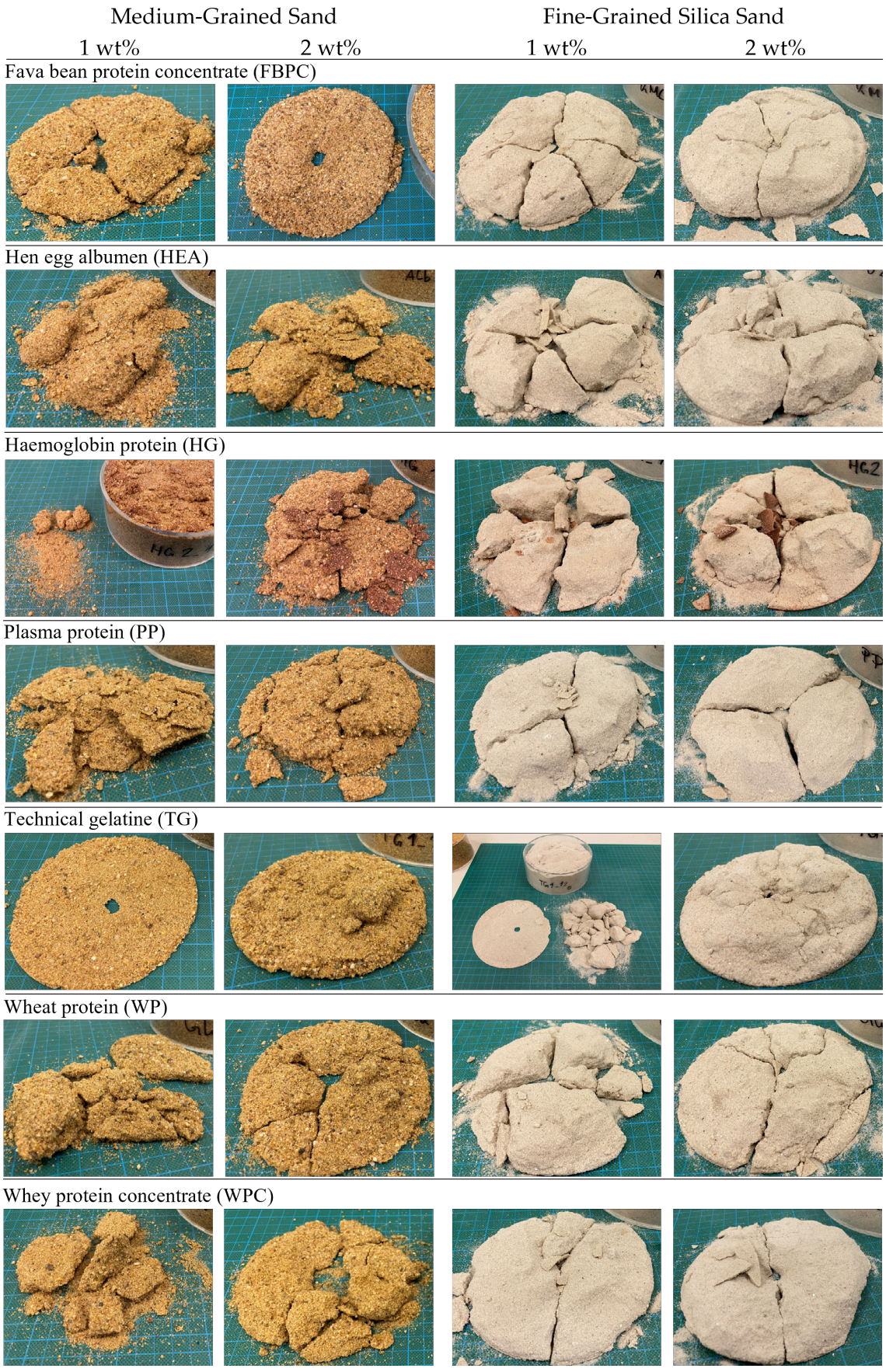


Figure 2.11: Examples of protein-induced crusts recovered from the samples (cf. Table A.6, p. 106).

Fine-Grained Silica Sand

The results of the crust thickness calculation are shown in Figure 2.12 (exact values are appended in Table A.5, p. 105). Exemplary depictions of the cured crusts are displayed in Figure 2.10 and Figure 2.11. The control group formed no recoverable crust, whereas all tested biopolymers formed crusts of varying thicknesses.

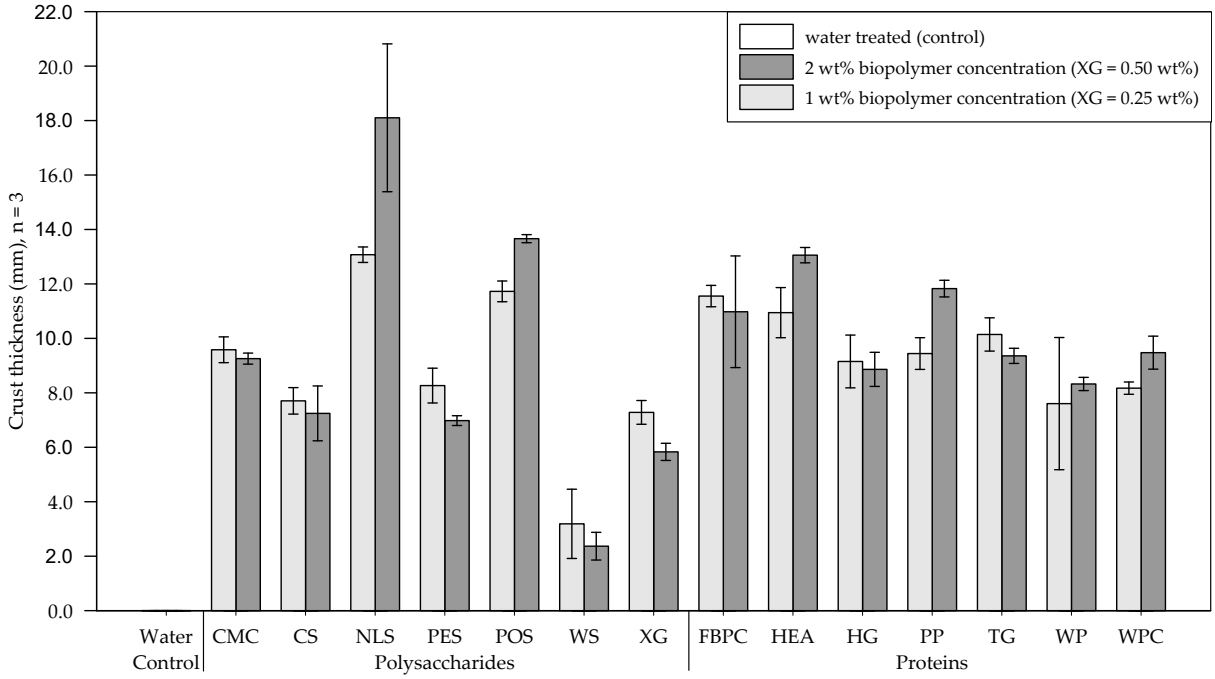


Figure 2.12: Mean thickness of crust formed on fine-grained silica sand samples. Biopolymers are grouped into polysaccharides and proteins with water as control. Tests were performed with three replicas ($n = 3$), with error bars indicating the standard deviation (SD). Note. The exact values of experimental results are appended in Table A.5, p. 105.

Polysaccharides. Polysaccharide applications at 1 wt% (XG = 0.25 wt%) formed crusts of varying thickness. WS formed only very thin and rather ductile crusts, while the remainder of the tested polysaccharide applications yielded significantly thicker crusts. Doubling the concentration increased the thickness of silica sand crusts amended with NLS and POS, while the other tested polysaccharide applications displayed decreased crust thicknesses. Notably, crusts formed because of treatment with WS even curled up throughout the curing period (Figure 2.10).

Proteins. Treatments at 1 wt% produced crusts of similar thicknesses, whereby amendments with FBPC, HEA, and TG formed the thickest crusts among the proteins tested. Doubling the concentration slightly decreased the thickness of crusts formed after treatment with FBPC, TG, and HG, whereas the other protein applications displayed slight increases in crust thickness.

Comparison of polysaccharide and protein treatments. At a biopolymer concentration of 1 wt% (XG = 0.25 wt%), protein amendments, on average, formed slightly thicker crusts than polysaccharide treatments. Doubling the concentration had a similar effect for most biopolymer applications, only slightly reducing or increasing the resulting crust thickness.

Statistical analysis. Two-way ANOVA (Table 2.5) shows that the biopolymer type has a significant effect on crust thickness among polysaccharides ($p < .001$) and proteins ($p < .001$), whereby the crust thickness differs significantly depending on the biopolymer type. By contrast, doubling the concentration has no significant effect (polysaccharides: $p = .288$, proteins: $p = .075$) on the

resulting crust thickness, as it only slightly increased or even decreased the crust thickness.

Conclusions. All biopolymers tested formed crusts on fine-grained silica sand. While the crust thicknesses were relatively uniform among the tested proteins, the tested polysaccharide amendments resulted in a greater variability. For all biopolymers, doubling the concentration had only a small effect on the resulting crust thickness.

2.4 Discussion

2.4.1 Moisture Retention Tests

Several studies have investigated the effect of different biopolymer types and concentrations on moisture retention of biopolymer-treated soils [94, 112–114, 116, 169, 196]. The studies found that biopolymer treatments enhance soil moisture retention, with the biopolymer type having a significant effect on the resulting moisture retention. Most studies concluded that moisture retention increases at higher biopolymer concentrations [112, 113, 116], although one study did not confirm this effect [114]. Soil type also appears to significantly influence the moisture retention that can be achieved by a biopolymer amendment [112]. In the following, the key trends of this study's results are discussed in the context of the previous literature. A more detailed discussion is limited by the significant differences in soil, treatment, and experimental setup among the studies.

Effect of Biopolymer Type

Medium-grained sand. The water-treated control group exhibited a higher moisture retention than several biopolymer treatments, which is not consistent with the existing literature [112, 114, 116, 197]. It is assumed that the relatively low viscosity of water allowed it to penetrate deeper into the medium-grained sand, making it less prone to evaporation. By contrast, the more viscous biopolymer solutions did not infiltrate as deeply into the sample, resulting in a higher evaporation rate.

Some biopolymer treatments significantly increased moisture retention (Figure 2.5), which is consistent with the findings of other studies examining the ability of biopolymers to improve soil moisture retention [112–114, 116, 129, 130, 198]. This increase is likely due to the high water-absorption capacity of the biopolymers, as well as the effects of the solution viscosity, bio-clogging, and crust formation. Low solution viscosity allows water molecules to infiltrate deeper into the soil, making them less susceptible to evaporation. Bio-clogging occurs when hydrated biopolymers clog the soil's pore space, reducing capillary conductivity and, thus, the evaporation rate [196, 199]. Additionally, biopolymer-induced surface crusts may act as barriers between moisture and air, slowing the evaporation rate [169, 200]. Biopolymers such as XG, PP, POS, and CMC did not significantly affect moisture retention (Figure 2.5), which does not correspond with the published literature [112, 113, 116]. Conversely to the biopolymer treatments that increased the moisture retention of medium-grained sand, it is likely that a low water-absorption capacity (PP and POS) or a relatively high viscosity (XG and CMC) contributed to a faster evaporation rate and thus lower moisture retention.

Fine-grained silica sand. Similar trends in moisture retention were found on fine-grained silica sand as on medium-grained sand, with some biopolymers decreasing it, some having no effect, and some increasing it significantly compared to the water-treated control group (Figure 2.6). In addition, as found for medium-grained sand, the control did not have the lowest moisture retention. The same reasons as identified for medium-grained sand likely caused these results.

Comparison of polysaccharides and proteins. On average, the well-performing proteins, such as FBPC, HEA, WP, and HG, achieved a higher moisture retention capacity than the well-

performing polysaccharides, such as CS, NLS, and WS (Figure 2.5 and 2.6). It is likely that this trend has been caused by the lower viscosity exhibited by most protein solutions and potentially a higher water-absorption capacity.

Effect of Biopolymer Concentration

Medium-grained sand. Increasing the biopolymer concentration had no significant effect on moisture retention (Figure 2.5 and Table 2.3). The published literature also reported mixed findings, with most studies concluding that higher biopolymer concentrations increase moisture retention [112, 113, 116], while one study could not confirm this observation [114]. For biopolymer applications that increased moisture retention (Figure 2.5), it is assumed that doubling the concentration amplified the effects of water absorption capacity, bio-clogging [196, 199], and crust formation [169, 200] (as discussed in previous paragraphs).

For some biopolymers, doubling the concentration had little effect on moisture retention or even caused it to decrease. Ding et al. [113] reported similar results when testing applications of lignosulphonates on red sand, with moisture retention only increasing noticeably up to a certain concentration. This suggests that each biopolymer has a specific threshold concentration, beyond which only minor changes or even a decrease in soil moisture retention occurs. This trend is likely related to an increase in biopolymer viscosity, which reduces infiltration depth and increases evaporation rate, resulting in the adverse effects of higher viscosity outweighing the positive effects of increased water absorption capacity, bio-clogging, and crust formation.

Fine-grained silica sand. On fine-grained silica sand, doubling the concentration resulted in a slight increase in moisture retention for most tested biopolymers (Figure 2.6 and Table 2.3), which agrees with previous studies [112, 113, 116]. It is believed that the same factors assumed for medium-grained sand caused these trends on fine-grained silica sand. Samples treated with XG and TG exhibited decreased moisture retention when the concentration was doubled, likely because of an increase in viscosity that limited the infiltration depth and, thus, increased the evaporation rate. CMC-treated samples showed no significant change, assumably because of the balancing of positive effects (e.g., increased water absorption, bio-clogging, and crust formation) and the negative effect of higher viscosity. Fine-grained silica sand samples, on average, exhibited a lower moisture-retention capacity than medium-grained sand samples (Figure 2.6) because of the higher hydraulic conductivity of medium-grained sand that enhanced the infiltration depth and decreased evaporation throughout the curing period.

2.4.2 Penetrometer Tests

Multiple studies performed penetrometer tests to investigate the effects of different biopolymers and concentrations on the penetration resistance of biopolymer-induced soil crusts [108–113, 116, 117]. A compilation of these studies' experimental results has been appended in Table A.7 (p. 107) and Table A.8 (p. 108). The results suggest that the biopolymer type has a significant effect on the crusts' penetration resistance, with some biopolymers forming firmer crusts than others. Increasing the concentration generally increases the penetration resistance [109, 114, 116], although one study found that this relationship plateaus at a specific concentration [110]. On sandy soil, biopolymers act by coating and binding sand particles together, forming a cross-linked 3D network that increases inter-particle cohesion [81]. In the following sections, the key trends of this study's results are discussed in the context of the previous literature, as a more detailed discussion is limited by the significant differences in soil, treatment, and experimental setup among the studies.

Effect of Biopolymer Type

Medium-grained sand. Penetrometer test results showed that all tested biopolymers formed crusts with differing penetration resistances, with the biopolymer type significantly affecting the penetration resistance (Table 2.4 and Figure 2.7). The water-treated control group formed no crust and endured a very low penetration resistance. These trends are consistent with findings from previous studies (Table A.7 (p. 107) and Table A.8 (p. 108)), which also showed that the water-treated control endured low penetration resistances relative to the biopolymer-treated samples.

Comparison with previous studies on XG, NLS, and CMC [109, 112] (cf. Table A.7 and Table A.8) reveals that XG forms stronger crusts than NLS, which agrees with this study's results (Figure 2.7). By contrast, Toufigh and Ghassemi [112] reported that CMC tends to form firmer crusts than XG, which contradicts the results of this study. This discrepancy may be due to the different XG types used in the two studies. The XG used in this study formed highly viscous, not-sprayable gels at concentrations > 0.5 wt%, while Toufigh and Ghassemi tested XG up to 1.5 wt% without reporting issues regarding the solution viscosity and spray-ability. Hence, it is likely that the XG used in this study had a higher gel strength and viscosity than the one tested by Toufigh and Ghassemi.

The starches (CS, POS, PES, and WS) also formed crusts, some with high penetration resistances. While the penetration resistance of starch-treated soil has not yet been investigated, other studies have already demonstrated their ability to improve soil mechanical properties. A wind tunnel study found that starch-treated soil exhibited reduced wind erosion [118], while other studies reported that starches and starch–xanthan blends enhanced the soil's geotechnical properties [96, 106, 161].

All tested proteins formed crusts, some of which had high penetration resistances (Figure 2.7). While previous studies have not investigated the crust strength of protein-treated soils, some studies demonstrated proteins' ability to enhance geotechnical soil properties [165, 169, 172, 201]. Analogous to PP, bovine plasma protein was found to increase the compressive strength of biopolymer-bound soil composites [165]; while corresponding to WPC, cottage cheese whey was found to improve aggregate stability and reduce furrow erosion [201]. Likewise, gelatine has been used as a constituent in the formulation of dust suppressants because of its film-forming properties [169, 172]. The remaining proteins tested in this study have not yet been tested regarding their ability to enhance soil properties but are commonly used in the food industry for their thickening, gelling, or water-retention abilities [202, 203].

Fine-grained silica sand. The penetrometer tests revealed that all biopolymer treatments formed crusts, with the biopolymer type significantly affecting the penetration resistance (Figure 2.8 and Table 2.4). This trend corresponds with previous research (Table A.7 and Table A.8). Compared to medium-grained sand, crusts on fine-grained silica sand, on average, had a higher penetration resistance. This can be attributed to the silica sands' smaller particle size, which results in a larger surface area, tighter packing, and lower hydraulic conductivity. As a result, the biopolymers coat a larger surface area, must bridge shorter distances between particles, and do not infiltrate as deep into the soil, and thus form a stronger crust.

Effect of Biopolymer Concentration

Medium-grained sand. Penetrometer test results showed that doubling the concentration significantly increased the penetration resistance of most biopolymers tested (Figure 2.7 and Table 2.4). This trend corresponds with previous research (Table A.7 and Table A.8) [109, 111–113]. As stated by Owji et al. [111], this is because higher biopolymer concentrations increase the thickness of the inter-particle bonds forming between the coated sand particles, which causes the

crust strength to increase. Doubling the concentration of WS and WPC only slightly increased the penetration resistance (Figure 2.7). The minor effect of WPC suggests that it generally has limited potential to enhance soil properties. Regarding WS, it is likely that its high viscosity limited the infiltration depth, leading to the presence of more biopolymer molecules in the pores than required to form a stable 3D network. Thus, for WS doubling, the concentration likely exceeded a threshold concentration, beyond which only minor increases in crust strength occur. This corresponds with findings of Lemboye et al. [110], who observed that applications of sodium alginate and pectin only increased penetration resistance up to 2 or 3 wt%.

Fine-grained silica sand. Doubling the concentration increased the penetration resistance of most biopolymers tested (Figure 2.8), similar to the findings on medium-grained sand (Figure 2.7) and the published literature (Table A.7 and Table A.8). WS and XG exhibit a different trend, as doubling their concentration resulted in decreased penetration resistances. This can be attributed to the high viscosities of their respective solutions, which limited infiltration depth and crust thickness, causing the crust to endure less load. For WS, the low infiltration and high local biopolymer concentration even caused the crust to curl up because of tension forces that occurred as the swollen biopolymers dehydrated and shrank (Figure 2.10).

Comparison of polysaccharides and proteins. On average, protein-treated samples exhibited larger incremental increases in penetration resistance than polysaccharide-treated samples upon doubling the concentration (Figures 2.7 and 2.8). Thereby, on medium-grained sand, some protein treatments only formed stable crusts at 2 wt%, while most tested polysaccharides formed stable crusts at 1 wt% on both soils (XG = 0.25 wt%). This suggests that for the tested polysaccharides, doubling the concentration likely surpassed a threshold beyond which only small increases in crust strength occur. As a result, proteins must be applied at higher concentrations to achieve comparable penetration resistances as polysaccharide-induced crusts on medium-grained sand.

2.4.3 Crust Thickness Measurements

Several studies have shown that the type and concentration of biopolymers significantly affect the thickness of biopolymer-induced soil crusts, and a compilation of their results has been appended for reference (Table A.9, p. 109) [64, 108, 110, 111, 113, 114]. Thereby, viscosity and the ability to enhance inter-particle cohesion influence the resulting crust thickness and depend on the biopolymer type and concentration. In the following, the main trends of this study's results are discussed in the context of previous studies. A more detailed discussion is limited by the significantly different soil types, treatments, and experimental setups used in previous studies.

Effect of Biopolymer Type

Medium-grained sand. The crust thickness measurements showed that all tested biopolymers produced crusts, with the biopolymer type significantly affecting the resulting crust thickness (Figure 2.9 and Table 2.5). These findings correspond with the published literature (Table A.9). In contrast to the other biopolymers, NLS, HEA, HG, and TG partially formed very thin and brittle crusts (Figures 2.10 and 2.11). Regarding NLS, this can be explained as previous studies found that lignosulphonates must be applied at concentrations > 2 wt% to enhance soil mechanical properties effectively [109, 119, 204]. The ability of HEA and HG to enhance soil mechanical properties has not yet been studied, but their treatments at 1 wt% and 2 wt% (only HEA) did not increase inter-particle cohesion sufficiently to form a competent crust.

Fine-grained silica sand. The test results showed that the biopolymer type significantly affects the crust thickness (Figure 2.12 and Table 2.5), which agrees with the existing literature (Table A.9). Compared to the other tested biopolymers, NLS, POS, HEA, and PP formed relatively thick crusts, likely because of a favourable combination of viscosity and bonding strength, allowing for a high infiltration depth and sufficient inter-particle cohesion to form a thick crust. By contrast,

WS and XG only formed thin crusts because of their high viscosity. Hence, on fine-grained silica sand, biopolymer viscosity is a limiting factor regarding the achievable crust thickness. Treatments on fine-grained silica sand generally formed thicker crusts than on medium-grained sand, as the finer particle size and tighter packing of the silica sand favour particle agglomeration and crust formation. In this context, NLS, HG, and HEA exhibited significant differences, forming only thin and brittle crusts on medium-grained sand but achieving considerably higher crust thicknesses on fine-grained silica sand.

Effect of Biopolymer Concentration

Medium-grained sand. The results of crust thickness measurements revealed that doubling the biopolymer concentration significantly affected crust thickness (Figure 2.9 and Table 2.5). For most polysaccharides, crust thickness only increased slightly or even decreased upon doubling the concentration, which corresponds with the published literature (Table A.9). This is likely because the increased viscosity limited the infiltration depth, resulting in a thinner crust. By contrast, NLS and POS treatment benefitted significantly from doubling the concentration, which increased the inter-particle cohesion sufficiently to form a thick crust.

In contrast to the polysaccharide treatments, doubling the concentration significantly increased the thickness of protein-induced crusts. This is because doubling the concentration increased inter-particle cohesion without limiting the infiltration depth. While most polysaccharides formed relatively thick crusts at 1 wt%, most proteins required concentrations of 2 wt% to achieve crusts of similar thickness. Thus, proteins must be applied at higher concentrations to achieve similar crust thicknesses as polysaccharide treatments.

Fine-grained silica sand. Results showed that doubling the concentration had no significant effect on the resulting crust thickness, leading only to slight increases or decreases (Figure 2.12 and Table 2.5). It appears that concentrations of 1 wt% are already sufficient to form a thick, stable crust, so doubling the concentration mainly resulted in adverse effects caused by the increase in viscosity.

2.4.4 Evaluation of Tested Biopolymers as Dust Suppressants

This study found that the tested biopolymers formed crusts with significantly increased penetration resistances relative to the water-treated control and, in part, enhanced moisture retention. As penetration resistance [108, 112, 180] and moisture retention [113] are commonly used indicators for assessing potential dust suppressants, it is concluded that most tested polysaccharides and proteins show potential as dust suppressants. XG was incorporated as a benchmark in the study, as it is the most widely studied biopolymer in soil stabilisation and dust control [82, 84]. The results on both tested soil types showed that some polysaccharides (CMC, CS, and WS) and proteins (FBPC, PP, and WP) achieved similar crust penetration resistances as XG (Figure 2.7 and Figure 2.8). However, it must be considered that XG was only tested at a quarter of the concentration of the other biopolymers.

Commercially available dust control products, such as chloride salts, petroleum-based products, and synthetic polymers, are effective dust suppressants but remain costly and can have adverse environmental effects [14, 205]. Thus, there is a need for affordable, environmentally friendly alternatives that are easy to apply. While approaches such as microbially induced carbonate precipitation show potential to mitigate wind erosion [65–67], their cultivation and application are challenging [69], rendering them not easy-to-apply off-the-shelf solutions. Alternatively, by-products and wastes from food processing have shown potential as dust suppressants [60, 62], but their inconsistent composition and dry-matter content may limit their application potential. By contrast, biopolymers show potential to meet the needs mentioned above.

This study and previous research [108, 110, 111, 144] have shown that biopolymers have potential as dust suppressants. Moreover, they are biodegradable [206], well-studied, and frequently applied in the food industry and medical applications[77, 78, 203]. The tested biopolymers have relatively low cost, are easily dissolvable in water, and can be applied using conventional water-spraying equipment. In addition, the tested biopolymers originate from botanical (corn, pea, wheat, cellulose, potato, and fava bean) and animal (pig, chicken, and cow) sources that are widely cultivated and bred. Consequently, biopolymers show potential as environmentally benign, readily available, low-cost, and easy-to-use alternatives to traditional dust suppressants. Further laboratory and field studies are needed to investigate their potential at different dosages and under realistic operating conditions to raise industry awareness.

2.5 Conclusion

This study examined the potential of 14 polysaccharides and proteins as dust suppressants by testing spray-on treatments at two different biopolymer concentrations on a medium-grained sand and a fine-grained silica sand. Moisture retention tests, penetrometer tests, and crust thickness measurements were performed, and the following conclusions were drawn:

1. Penetrometer test results on biopolymer-treated medium-grained sand ranged from 1.7 to 34.0 N (control = 1.5 N) and on fine-grained silica sand from 6.7 to 37.9 N (control = 1.7 N), respectively. The results showed that all tested biopolymers formed crusts with significantly differing penetration resistances depending on the biopolymer type ($p < .05$). Increasing the biopolymer concentration significantly increased the penetration resistance on medium-grained sand ($p < .001$). In contrast, on fine-grained silica sand, it only increased the penetration resistance of protein treatments significantly ($p < .001$). Proteins achieved similar penetration resistances as polysaccharides but required higher concentrations.

2. Moisture-retention test results on medium-grained sand ranged from 3.4 to 19.5 wt% (control = 6.9 wt%) and on fine-grained silica sand from 1.0 to 18.2 wt% (control = 2.5 wt%). On both tested soil types, the biopolymer type had a significant effect ($p < .001$) on the samples' moisture retention, resulting in it decreasing or increasing relative to the water-treated control. Increasing the concentration increased moisture retention of protein-treated fine-grained silica sand samples significantly ($p < .001$).

3. The thicknesses of crusts formed on biopolymer-amended medium-grained sand samples ranged from 0.3 to 8.8 mm (control = 0 mm) and on fine-grained silica sand from 3.2 to 18.1 mm (control = 0 mm). The results showed that the different biopolymers formed crusts of varying thicknesses, with the biopolymer type significantly affecting the crust thickness ($p < .001$). On medium-grained sand, doubling the concentration only had a significant effect for protein amendments ($p < .001$) and resulted in the crust thickness increasing. On fine-grained sand, increasing the concentration slightly reduced the crust thickness of most treatments because of a lower infiltration depth.

The results of this study demonstrate that the tested polysaccharides and proteins have the potential to be applied as dust suppressants in industries such as mining. Thereby, biopolymers can contribute to reducing the industry's environmental and human health impacts.

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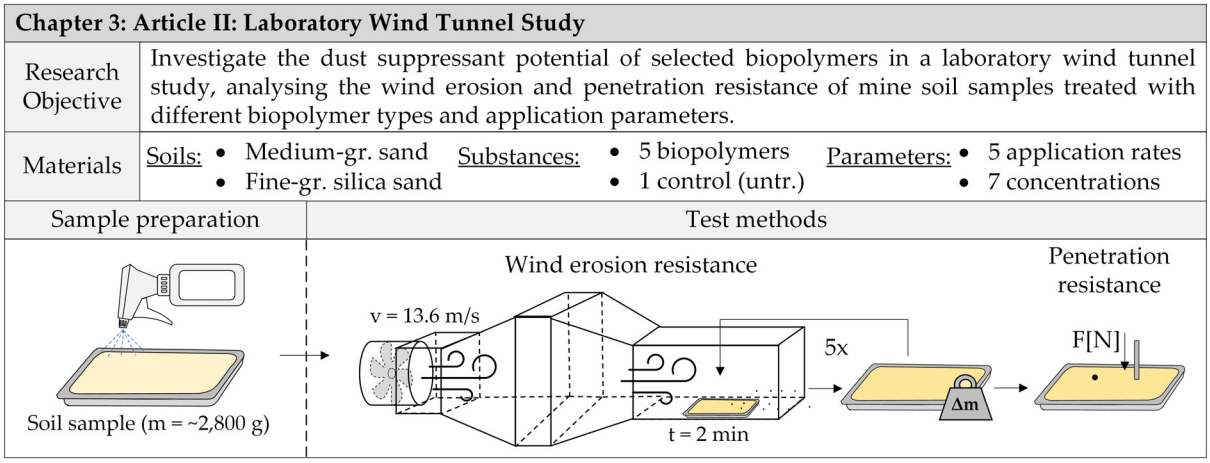
Chapter 3

Article II: Laboratory Wind Tunnel Study

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



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3.1 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 [6, 25, 35, 173, 207]. Thus, 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 synthetic polymers are effective, they are often costly, can have adverse environmental effects [14, 205], may not be degradable, or their toxicity and potential health effects are largely unknown [15]. 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 mainly focused on biopolymers [1, 109–112], food processing by-products and wastes [58, 60–62], and enzyme or microbial-induced carbonate precipitates (EICP and MICP) [64, 66, 67]. Although EICP and MICP have shown high effectiveness and durability, their cultivation, application, and rejuvenation remain difficult [69] and may require professional staff. While food processing by-products and wastes have demonstrated potential in several studies [58, 60–62], their inconsistent composition and dry-matter content limit their application potential. On the other hand, biopolymers have displayed potential as dust suppressants (e.g., [64, 110, 112–114, 142]) 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) [110, 112, 142], while research on polysaccharides and especially proteins that can be cultivated in continental climate remains underrepresented [1]. 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. [1], 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 [112, 113, 180], 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 [112, 118] and enable comparison 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, and application rates 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 determining 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.

3.2 Materials and Methods

3.2.1 Soils

Two mine soils, which were already used by a previous study by Sieger et al. [1], were employed by this study: (a) A medium-grained sand ($D_{50} = 0.63\,mm$, $C_u = 2.73$), classified according to the USCS as poorly graded sand (SP) mainly consisting of quartz and plagioclase, and (b) a 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. [1].

3.2.2 Biopolymers

In a previous study, Sieger et al. [2] investigated the potential of 14 polysaccharide and protein biopolymers as dust suppressants. Five biopolymers that showed high 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) [208]. In addition, XG is a widely studied biopolymer in soil stabilisation (e.g., [82, 84, 138]).
- *Corn starch (CS).* Pregelatinised 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 in light-yellowish granules, and has a moisture content of 8.6 wt%. This polysaccharide is applied in the food, paper, textile, and other industries due to its diverse properties, such as mechanical strength and viscosity [209].
- *Fava bean protein concentrate (FBPC).* Enzyme-activated FBPC was obtained from Aljoa-Starkelsen (LV), comes as 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 [202].
- *Wheat protein (WP).* Degraded wheat protein without viscoelastic properties was obtained from Kröner Stärke GmbH (DE), comes in a yellowish powder, and has a moisture content of 6.0 wt%. It is primarily used as a meat replacement and for sports nutrition.

3.2.3 Laboratory Experiments

Laboratory experiments comprised two consecutive test phases, whose sample programs are listed in Table 3.1 (Phase 1) and Table 3.2 (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 and pocket penetrometer testing. Phase 1 investigated the effect of the biopolymer concentration on the wind-induced soil loss and the crust penetration resistance, testing seven different biopolymer concentrations at a fixed application rate of $0.5\,L/m^2$ (Table 3.1). 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 (cf. Glossary). 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 3.2).

Table 3.1: Sample program of Phase 1, which investigated the effect of the biopolymer concentration on the wind erosion resistance and the crust penetration resistance.

Biopolymer/ Control	Concentration (wt%)										Application Rate (L/m²)
	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 ≤ 0.75 wt% but at finer intervals, as higher concentrations yielded too viscous solutions to be sprayable.

Table 3.2: Sample program of Phase 2, which tested the effect of the application rate on wind erosion and crust penetration resistance. Biopolymer concentrations were selected based on the results of Phase 1

Biopolymer/ Control	Concentration (wt%)		Application Rate (L/m²)			
	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/m² was not tested again, as it was already included in Phase 1.

Sample Preparation

336 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 $176 \times 325 \times 40$ mm and a sample surface area of 0.043 m² (Figure 3.1a). Samples were gently shaken to ensure slight and uniform compaction and levelled with 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 3.1b). The biopolymer's respective moisture content (see section 3.2.2) 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 3.1c). Similar to Sieger et al. [1], a 3D-printed splash guard prevented the biopolymer solutions from inadvertently touching the weighing plate of the scale and distorting the scale readings.

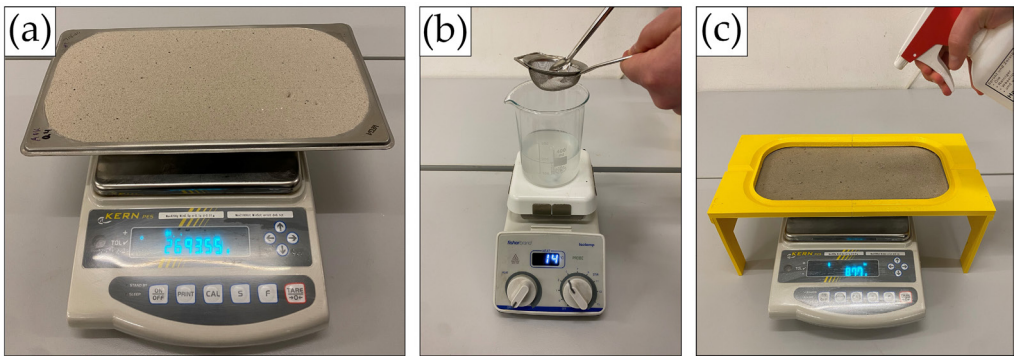


Figure 3.1: Sample preparation. (**a**) Weighing of dry sample, (**b**) preparation of biopolymer solution, (**c**) gravimetric spray-on application with splash guard.

Wind Tunnel Tests

Wind tunnel tests were performed at the Institute of Mineral Resources Engineering (RWTH Aachen University, GER) with the wind tunnel setup used by Freer et al. [61, 62] (Figure 3.2). 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 ambient temperature ($21 \pm 1\,°C$) and humidity ($45 \pm 2.5\,\%$) 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 3.2f). Samples were weighed before and after each wind tunnel cycle using a precision scale (KERN PES 4200-2M) to calculate the gravimetric soil loss.

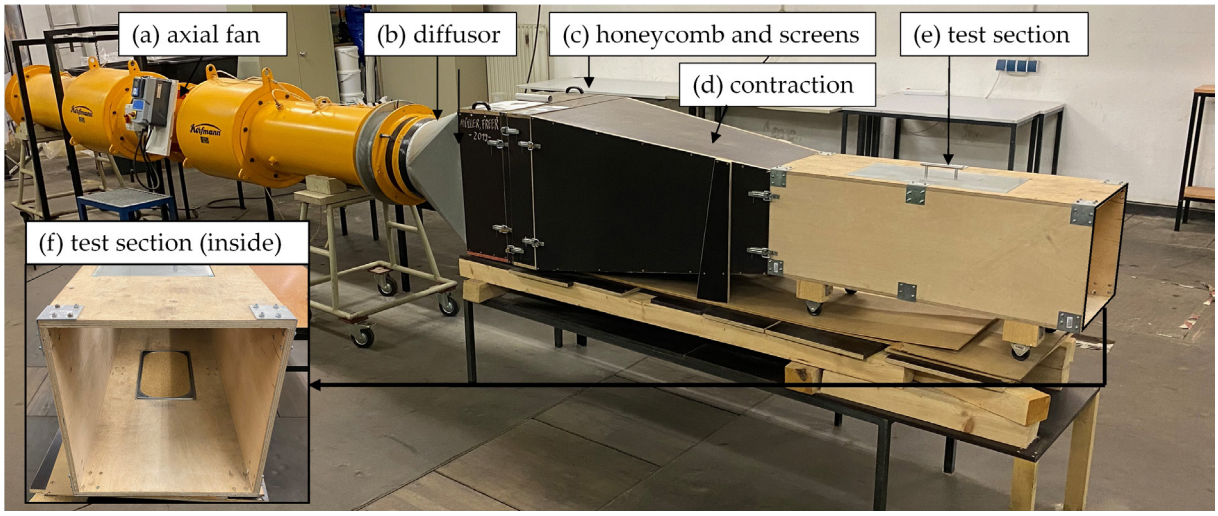


Figure 3.2: Wind tunnel and wind tunnel test section, showing individual components (**a**) to (**f**). Adapted from Freer et al. [61, 62].

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* (cf. Glossary) relative to the control group (C) was established for each biopolymer treatment according to Equation (3.1):

$$\text{Dust control effectiveness } (\%) := 1 - \frac{\triangle m_{BP}}{\triangle m_c} \tag{3.1}$$

where $\triangle m_{BP}$ denotes the total soil loss of the biopolymer-treated sample (g/m^2), and $\triangle m_C$ denotes the total soil loss (g/m^2) that occurred on C. This allows for comparing the results with previous studies investigating the dust control effectiveness of amended soils (e.g., [64, 119, 171, 210]).

Penetrometer Tests

After performing the last wind tunnel cycle, the penetration resistance (the crust strength) of the samples' crusts was measured with a hand-held dial-type pocket penetrometer (H 4205) (Figure 3.3a,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 (top and bottom) at an angle of 90 ° by gradually increasing the load until the crust ruptured.

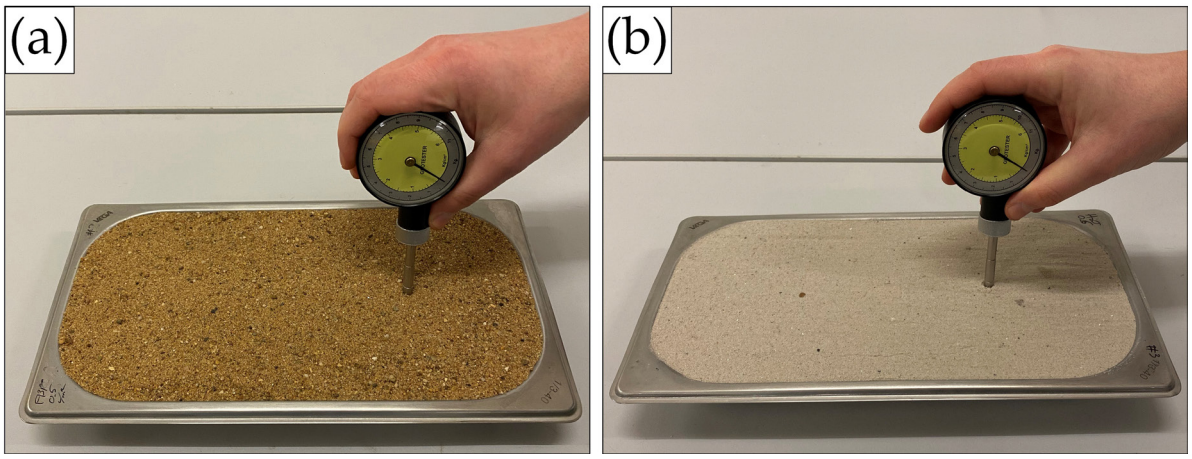


Figure 3.3: Hand-held pocket penetrometer testing. (**a**) medium-grained sand sample, (**b**) fine-grained silica sand sample.

3.3 Results

3.3.1 Wind Tunnel Tests

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

Medium-grained sand. Figure 3.4 shows the wind-induced soil losses of medium-grained sand samples treated with different biopolymer types and concentrations (numerical values are appended in Table B.1, p. 111). All biopolymer treatments significantly reduced the wind-induced soil loss compared to the control (C). The soil loss decreased at increasing concentrations until reaching a 'plateau concentration' beyond which only marginal reduction in soil loss occurs. At lower concentrations, the polysaccharides (XG, CS, and CMC) tended to perform better than the tested proteins (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% that gradually reduced as concentration increased. WP and CMC amended samples showed no improvement in soil losses at 0.50 wt%, while FBPC plateaued at 0.75 wt%.

Fine-grained silica sand. The wind-induced soil losses of biopolymer-amended fine-grained silica sand samples are shown in Figure 3.5 (numerical values are appended in Table B.1). Compared to the control, which experienced substantial soil loss, all biopolymer treatments significantly reduced wind-induced soil losses. As observed on medium-grained sand, the soil loss decreases as the biopolymer concentration increases until reaching a 'plateau concentration'. Again, the protein amendments (especially FBPC) showed noticeably higher soil losses at lower concentrations than polysaccharide-treated samples. Samples amended with XG displayed low soil loss at 0.05 wt%, reaching a stagnation concentration at 0.13 wt%. By contrast, CS, CMC and WP treatments showed moderately higher soil losses at 0.13 wt% that decreased at higher concentrations. While CS achieved its stagnation level at 0.25 wt%, CMC achieved it at 0.50 wt% and WP at 1.25 wt%, respectively. Lastly, amendments with 0.13 wt% FBPC displayed the highest soil loss but reduced significantly as the concentration increased until plateauing at 1.0 wt%.

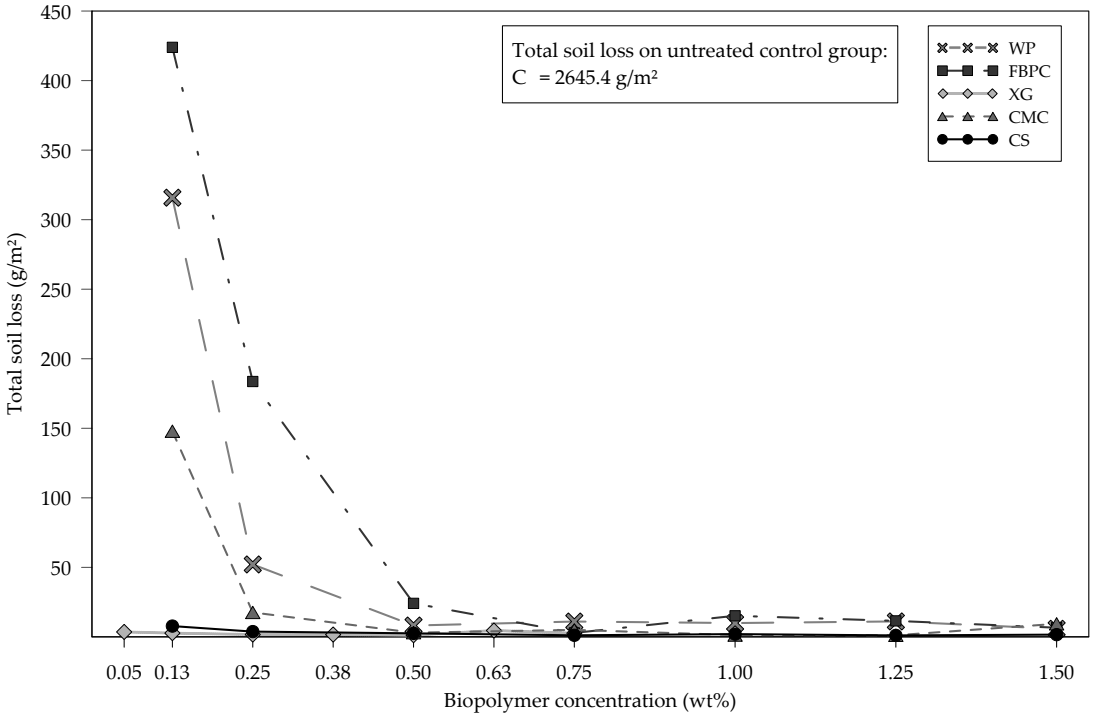


Figure 3.4: Total soil loss (g/m²) of medium-grained sand samples treated with different biopolymer concentrations. Tests were performed in triplicate ($n = 3$). Note. Numerical data (mean (M) and standard deviation (SD)) are appended in Table B.1, p. 111. Error bars representing the SD have been deliberately omitted for better legibility.

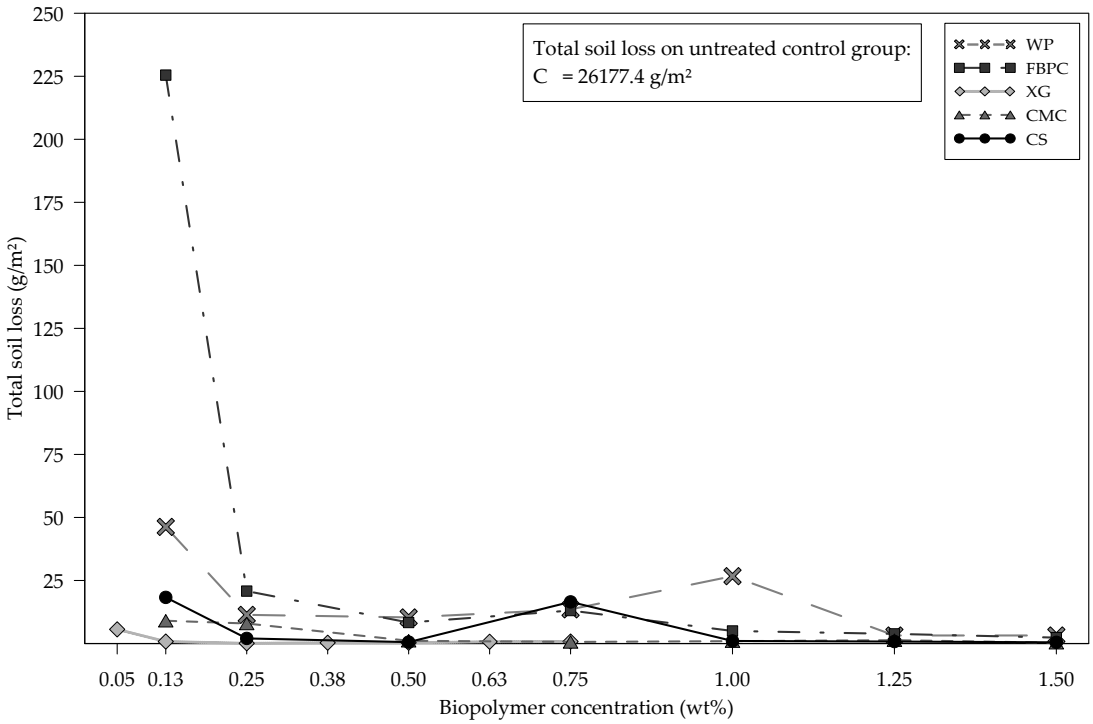


Figure 3.5: Total soil loss (g/m²) of fine-grained silica sand samples treated with different biopolymer concentrations after the fifth wind tunnel cycle. Tests were performed in triplicate ($n = 3$). Note. Numerical data (mean (M) and standard deviation (SD)) are appended in Table B.1, p. 111. Error bars representing the SD have been deliberately omitted for better legibility.

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

Medium-grained sand. Figure 3.6 displays the results of the wind tunnel tests conducted with samples treated at different application rates and the biopolymers' respective plateau concentrations (see Table 3.2). The corresponding dust control effectivenesses are appended in Table B.3, p. 112. While the control group demonstrated considerable soil loss, all biopolymer-treated samples, regardless of the biopolymer type and application rate, displayed only marginal soil losses and achieved dust control effectivenesses $> 99\,\%$. Upon closer examination of the biopolymer treatments, it becomes evident that some biopolymers performed slightly better than others. 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.

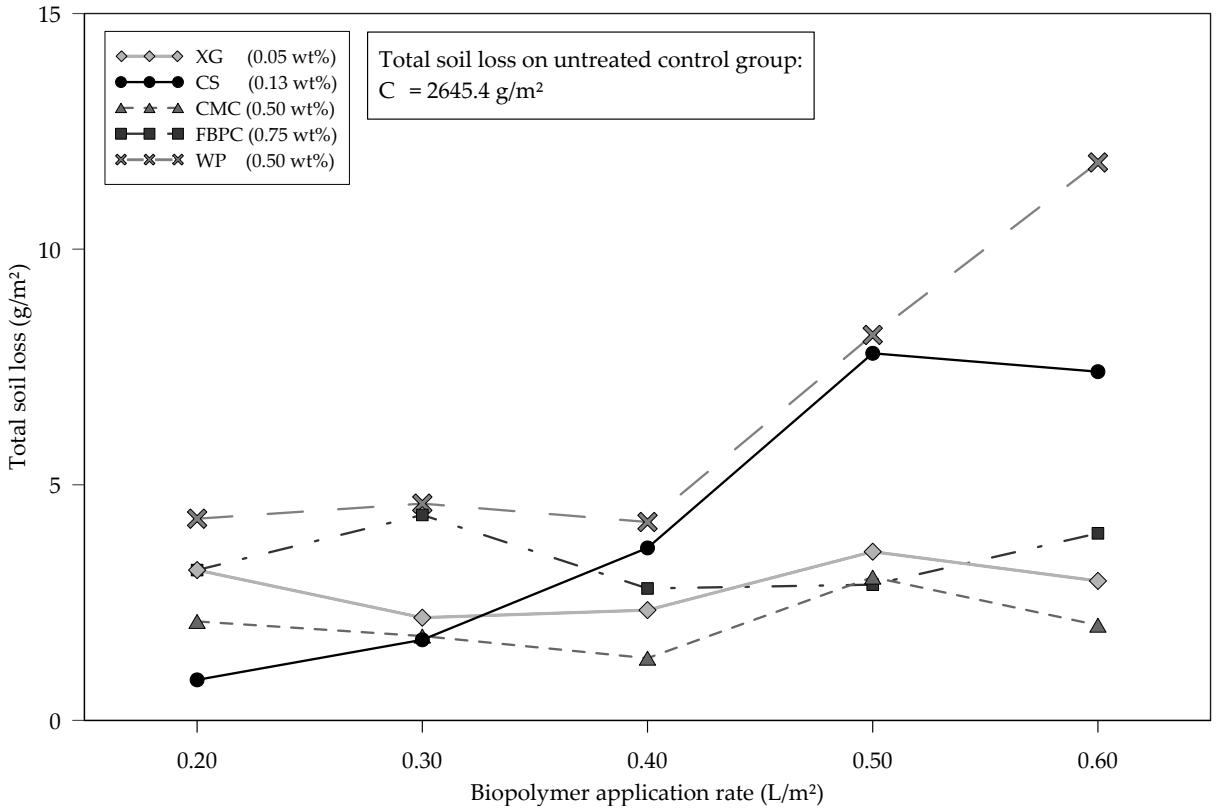


Figure 3.6: Total soil loss (g/m²) of medium-grained sand treated at their 'plateau' concentration at different biopolymer application rates. Tests were performed in triplicate ($n = 3$). Note, numerical data (mean (M) and standard deviation (SD)) are appended in Table B.2, p. 112. Error bars representing 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 3.2) are shown in Figure 3.7. Compared to the control group, which exhibited substantial soil loss, all biopolymer treatments significantly enhanced the wind erosion resistance, irrespective of the biopolymer type and application rate, achieving dust control effectivenesses $> 99\,\%$ (Table B.2). The total soil loss of samples treated with CS, WP and CMC was relatively stable as the application rate increased, while XG-amended samples showed slightly stronger fluctuations in soil loss. By contrast, treatments with FBPC benefitted noticeably from increasing the application rate to $0.3\,\mathrm{L/m^2}$, beyond which only minor changes occurred.

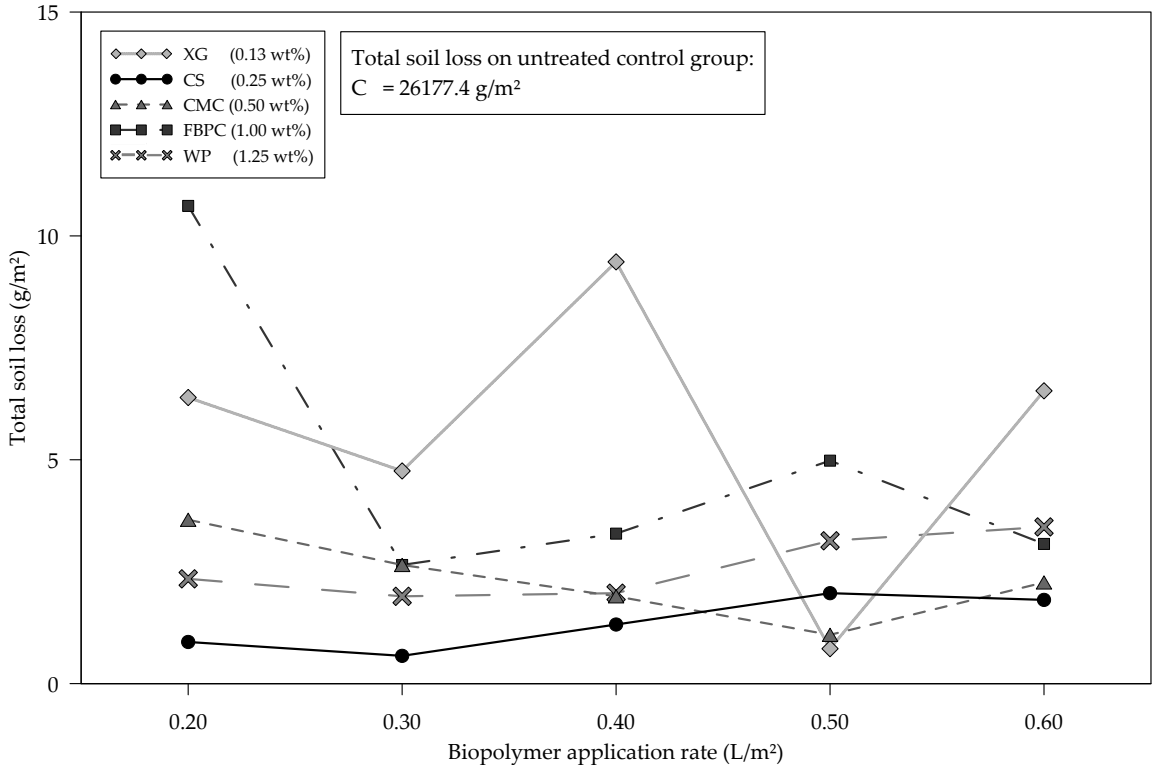


Figure 3.7: Total soil loss (g/m²) of fine-grained silica sand samples treated at their 'optimum' concentration at different biopolymer application rates after the fifth wind tunnel cycle. Tests were performed in triplicate ($n = 3$). Note, numerical data (mean (M) and standard deviation (SD)) are appended in Table B.2, p. 112. Error bars representing the SD have been deliberately omitted for better legibility.

3.3.2 Penetrometer Tests

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 3.8 (see Table B.4 for numerical values). The control group showed no penetration resistance (lower reading limit of pocket penetrometer = 0.5 N). By contrast, all biopolymer treatments formed crusts, with the penetration resistance tending to increase as the concentration increases. 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 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.

Fine-grained silica sand. Figure 3.9 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 biopolymer treatments formed crusts with penetration resistance tending to increase at higher concentrations. Polysaccharide treatments (XG, CMC, and CS) generally displayed higher penetration resistances than protein treatments (WP and FBPC). XG formed relatively strong crusts at the lower tested concentrations and is only surpassed by CMC and CS at concentrations ≥ 0.75 wt% (XG ≥ 0.38 wt%). The penetration resistance of WP- and FBPC-amended samples plateaus at concentrations of 0.50 and 0.75 wt%, respectively. In contrast, XG- and CMC-amended samples peaked at 0.63 and 1.50 wt%, respectively, after stagnating at lower concentrations.

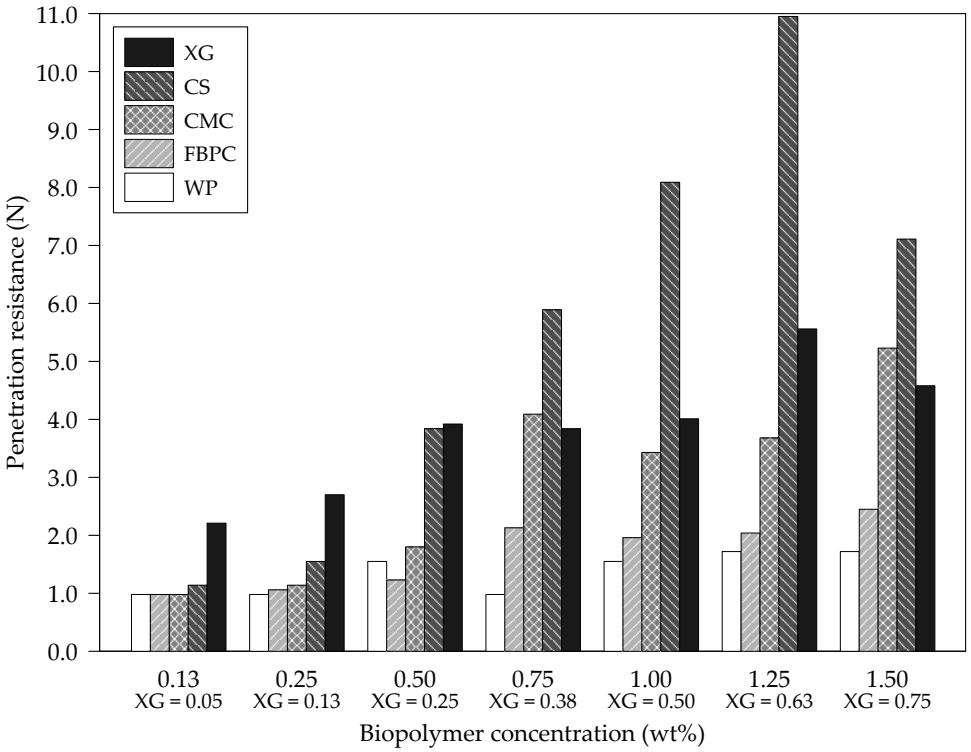


Figure 3.8: Penetration resistance of crusts after last wind tunnel test on day 28 on medium-grained sand. Penetration resistance tests were performed with six replicates ($n = 6$) with two penetrations per sample. The numerical data (mean (M) and standard deviation (SD)) are appended in Table B.4, p. 113.

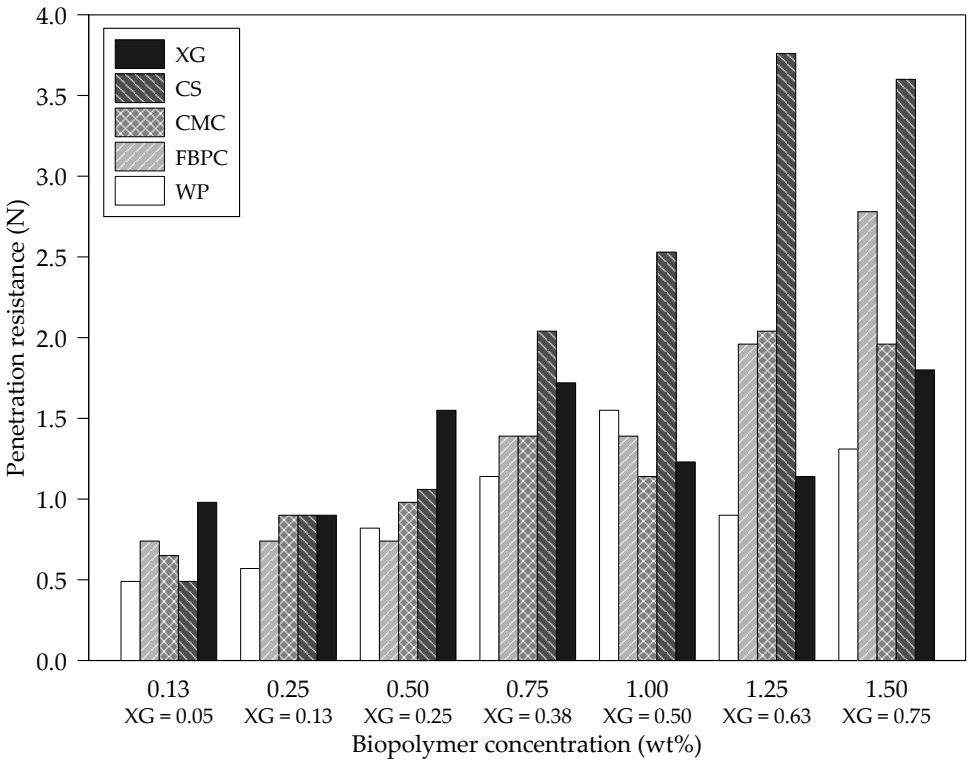


Figure 3.9: Penetration resistance of crusts after last wind tunnel test on day 28 on fine-grained silica sand. Penetration resistance tests were performed with six replicas ($n = 6$) with two penetrations per sample. Numerical data (mean (M) and standard deviation (SD)) are appended in Table B.4, p. 113.

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 3.10. The control group showed no measurable penetration resistance, while all biopolymer treatments formed crusts. Although the absolute crust strengths of the samples were relatively weak, penetration resistances generally increased with higher application rates. Despite differing plateau concentrations, most 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 with higher application rates. Contrarily, WP and CS treatments did not exhibit a clear trend, with the crust strength of CS-treated samples peaking at 0.2 L/m² and WP-treated samples at 0.5 L/m², respectively.

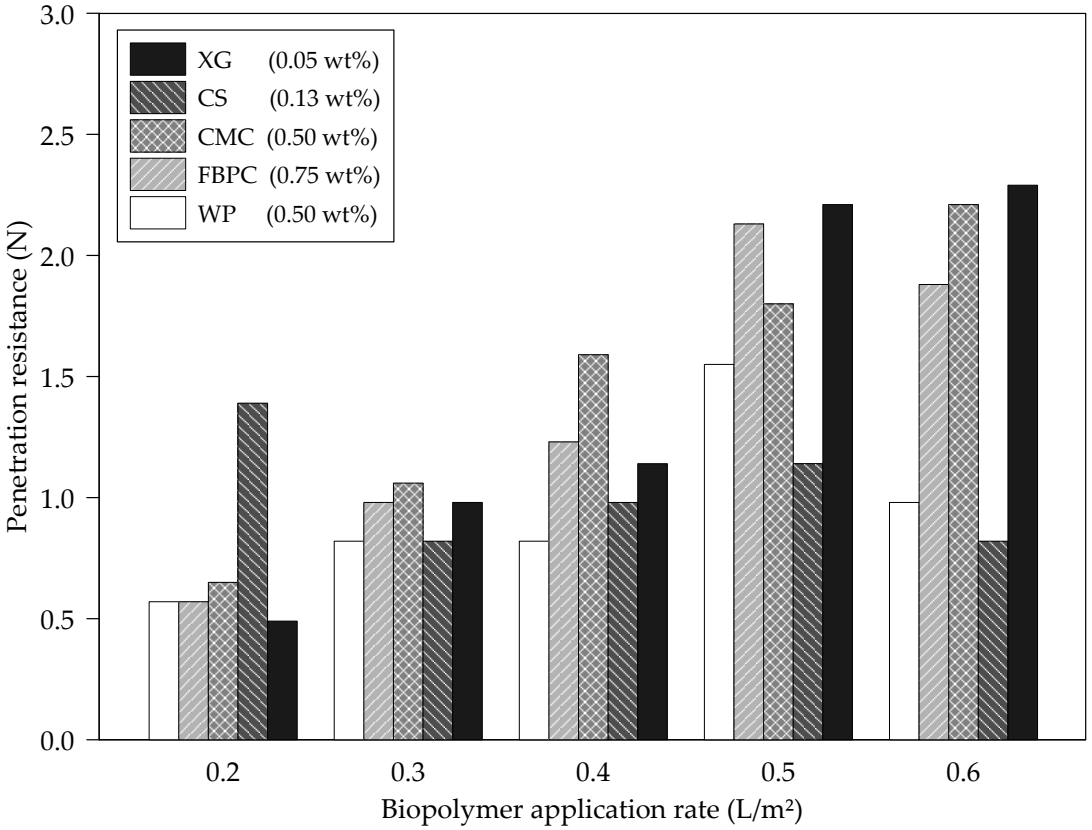


Figure 3.10: Penetration resistance of crusts from medium-grained sand samples, performed after the fifth wind tunnel cycle on day 28. Biopolymers were applied at their respective 'plateau' concentration determined in Phase 1. Each of the three prepared samples was penetrated at the top and bottom of the centre ($n = 6$). Error bars indicate the standard deviation (SD). The numerical results are appended in Table B.5, p. 113.

Fine-grained silica sand. Figure 3.11 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 biopolymer treatments exhibited relatively low penetration resistances, mostly ranging from 0.5 to 1.5 N, with the penetration resistance increasing slightly with higher application rates. Despite the differing plateau concentrations used for the different biopolymer types, most treatments resulted in similar penetration resistances at the respective application rates. The proteins (FBPC and WP) and CMC produced the strongest crusts but were also applied at higher concentrations than CS and XG.

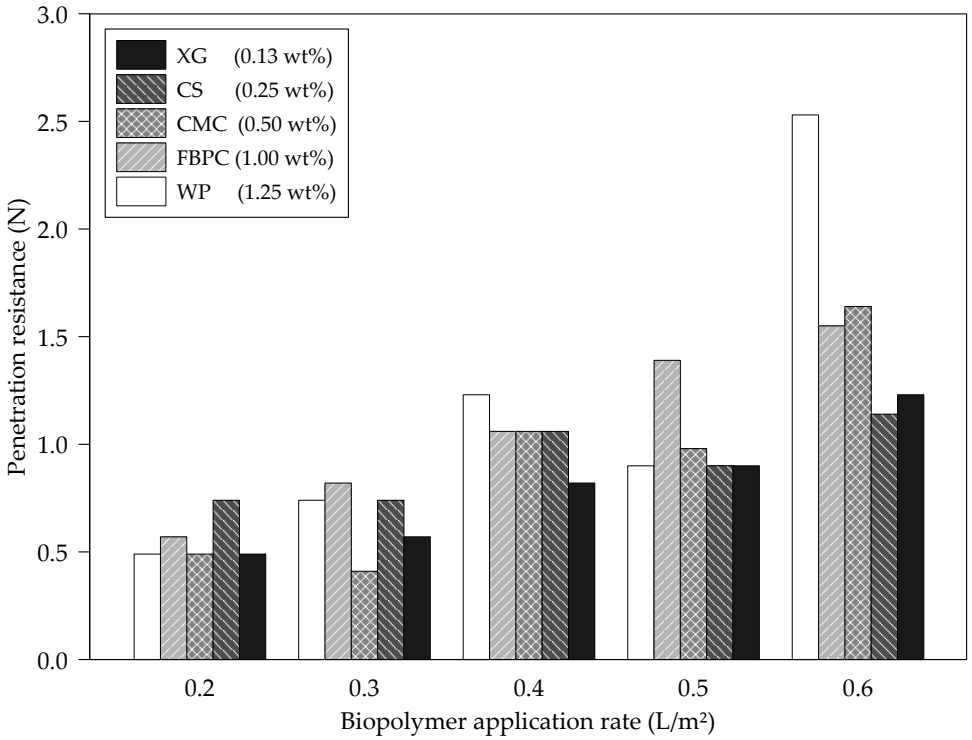


Figure 3.11: Penetration resistance of crusts from fine-grained silica sand samples, performed after the fifth wind tunnel cycle on day 28. Biopolymers were applied at their 'plateau concentrations' determined in Phase 1. Each of the three prepared samples was penetrated at top and bottom of the centre ($n = 6$). Error bars indicate the standard deviation (SD) and numerical results are appended in Table B.5, p. 113.

3.3.3 Statstical Analysis

Wind tunnel tests – Phase 1. Results of the two-way ANOVA (Table 3.3) of the wind tunnel test data reveal that on both tested soil types, biopolymer type ($p < .001$) and concentration ($p < .001$) have a significant effect on wind-induced soil loss. Some biopolymer types achieve higher wind erosion resistance than others, and the soil loss generally decreases as the concentration increases until reaching a plateau concentration.

Table 3.3: Results of two-way ANOVA ($\alpha = .05$) 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	< .001	21,479.42	4	5,369.85	53.5	< .001
Concentration	380,509.42	6	63,418.24	60.9	< .001	40,628.28	6	6,771.38	67.5	< .001
Interaction	355,037.08	24	14,793.21	14.2	< .001	86,459.69	24	3,602.49	35.9	< .001
Error	72,859.77	70	1,040.85			7,025.46	70	100.36		

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

Wind tunnel tests – Phase 2. For medium-grained sand, results of the two-way ANOVA show that the biopolymer type ($p < .001$) and application rate ($p < .001$) significantly affect the wind erosion resistance (Table 3.4). Some biopolymer types perform slightly better than others, and the soil loss increases slightly as the application rate increases. On fine-grained silica sand, only the biopolymer type ($p < .050$) appears to have a significant effect, unlike the application rate ($p = .568$), exhibiting no observable trend.

Table 3.4: Results of two-way ANOVA ($\alpha = .05$) 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	$< .001$	196.99	4	49.25	2.6	$< .050$
Application rate	160.87	6	40.22	16.1	$< .001$	55.96	6	13.99	0.7	0.568
Interaction	124.3	24	7.77	3.1	$< .050$	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, results of the two-way ANOVA reveal that the biopolymer type ($p < .001$) and concentration ($p < .001$) have a significant effect on the samples' penetration resistance (Table 3.5). Some biopolymer types achieve higher penetration resistances than others, and the penetration resistance generally increases with higher concentrations.

Table 3.5: Results of two-way ANOVA ($\alpha = .05$) 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	$< .001$	26.4	4	6.61	20.2	$< .001$
Concentration	332.3	6	55.38	38.2	$< .001$	65.3	6	10.9	33.2	$< .001$
Interaction	283.7	24	11.82	8.16	$< .001$	37.8	24	1.57	4.8	$< .001$
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 ($p < .001$) and the fine-grained silica sand ($p < .05$) (Table 3.6). Also, the application rate significantly affects the penetration resistance ($p < .001$), with the penetration resistance generally increasing at higher application rates.

Table 3.6: Results of two-way ANOVA ($\alpha = .05$) 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	$< .001$	2.66	4	0.67	5	$< .05$
Application rate	23.62	6	5.9	36.8	$< .001$	20.9	6	5.23	39.6	$< .001$
Interaction	14.79	24	0.92	5.8	$< .001$	7.16	24	0.45	3.4	$< .001$
Error	20.07	70	0.16			16.5	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 on medium-grained sand ($r(106) = -.81$, $p < .001$) and a moderate negative correlation on fine-grained silica sand ($r(106) = -.51$, $p < .001$), indicating that the soil loss tends to decrease as the penetration resistance increases. For the results of Phase 2, only weak negative correlations on medium-grained sand ($r(80) = -.2$, $p = .123$) and fine-grained silica sand ($r(80) = -.1$, $p = .296$) were found.

3.4 Discussion

3.4.1 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 [81]. 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 [61, 110–114, 116, 118, 142, 143, 211, 212]. The key results of these studies have been compiled and appended in Table B.6 (p. 114) and are recommended for reference 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.

Effect of Biopolymer Type

The results showed that all tested biopolymer types significantly enhanced the samples' wind erosion resistance on both tested soil types (Figure 3.4 and Figure 3.5). When applied at their respective plateau concentration, all biopolymers exhibited dust control effectivenesses $> 99\,\%$ with no distinct differences among the tested biopolymer types (Table B.3, p. 112). As can be seen in Table B.6, these trends are consistent with most previous research, which also found that all biopolymers tested significantly improved soil wind erosion resistance and achieved effectivenesses $> 90\,\%$ (with many $> 95\,\%$). However, some previous studies reported lower effectiveness rates than 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 [112], Chen et al. [116], and Ayeldeen et al. [118] performed wind tunnel tests at significantly higher velocities (20 m/s in [112], 17.6 m/s in [116], and 41.6 m/s in [118]) 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 [113, 114, 118] or incorporating saltation bombardment [111], which allowed revealing more distinct differences among the biopolymer types.

While all tested protein and polysaccharide treatments significantly enhanced the soil's wind erosion resistance, at the lower tested concentrations, protein-amended samples (FBPC and WP) exhibited noticeably higher soil losses on both tested soil types than the polysaccharides (XG, CS and CMC) (cf. Figure 3.4 and Figure 3.5). As previous wind tunnel studies have not examined the wind erosion resistance of protein-amended soils, this observation can only be compared with a previous study investigating the crust strength of biopolymer-treated soil. Here, Sieger et al. [1] found that polysaccharide treatments tend to form stronger crusts than proteins, which is also consistent with the results of the pocket penetrometer tests conducted by this study (Figure 3.8 and Figure 3.9). Thus, it is believed that the tested polysaccharides have better inter-particle cohesion and, hence, crust-forming properties than the tested proteins.

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 3.3). This finding is consistent with existing literature, which also found that some biopolymer types achieve higher dust control efficiencies than others (Table B.6). This study showed that XG performs better than CMC and CS when applied at similar concentrations (Figure 3.4 and Figure 3.5). However, Toufigh and Ghassemi [112] found that CMC treatments achieve lower

soil losses than XG, which could be due to the different XG types used in the two respective studies. While Toufigh and Ghassemi [112] applied XG at up to 1.5 wt% without reporting difficulties regarding the spray-ability, the viscosity of the 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. [118] indicated that corn starch performed better than XG. 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.

Effect of Concentration

On both tested soil types, the experimental results showed that the wind-induced soil loss decreases significantly with increasing biopolymer concentration until reaching a 'plateau concentration', beyond which only marginal changes occur (Figure 3.4 and Figure 3.5). The two-way ANOVA also reveals that the concentration has a significant effect on wind-induced soil loss (Table 3.3). These trends are generally consistent with existing literature (e.g., [110, 111, 113, 114] and Table B.6), which also reported that the soil loss decreases with increasing biopolymer concentration until reaching a plateau. Only one exception was reported by Dagliya et al. [142], 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 comparing the effectiveness of the different biopolymer types with each other. While on 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 material-efficient than the other biopolymers tested.

Effect of Application Rate

The experimental results showed that irrespective of the application rate tested, all biopolymer treatments considerably reduced the wind-induced soil loss on both tested soil types (Figure 3.6 and Figure 3.7). This suggests that at their respective plateau concentrations, all biopolymers were able to effectively agglomerate particles on the sample surface to a crust, already at a low application rate of 0.2 L/m². Similar trends have also been reported by Owji et al. [111] and Kavazanjian et al. [143] (Table B.6). Both studies found that increasing the application rate only slightly reduced 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. [110] showed that increasing the application rate of 0.5 wt% Acacia gum treatments significantly reduced the soil loss, whereas equal treatments with Sodium alginate and Pectin already displayed high wind erosion resistance at the lower application rate. Likewise, Freer et al. [61] 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 [110, 111, 143], 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 $> 0.4\,\mathrm{L/m^2}$, with the two-way ANOVA indicating that the application rate has a significant effect ($p < .001$) (Table 3.4). This minor trend contradicts 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 on 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 relevant for further potential field applications.

Evaluation of the Dust Control Effectiveness

On both tested soil types, the results demonstrated that application at the biopolymers' respective plateau concentrations resulted in high dust control effectivenesses $> 99\,\%$, even at a low application rate of $0.2\,\mathrm{L/m^2}$ (see Figure 3.6, Figure 3.7, and Table B.3, p. 112). 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 comparing these results with previous studies, due to 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 $0.6\,\mathrm{L/m^2}$, but also less demanding wind tunnel conditions (horizontal sample placement and 13.6 m/s). Two studies performed wind tunnel tests with similar parameters [143, 212]. Kavazanjian et al. [143] tested Xanthan gum (0.1 wt% and $0.4\,\mathrm{L/m^2}$) and Chitosan (0.1 wt% and $0.5\,\mathrm{L/m^2}$) on horizontally placed sand with silt (SM) samples at 7.2 m/s and also reported effectiveness $> 99\,\%$ (Table B.6, p. 114). Similarly, Erci et al. [212] tested a commercial hydrogel (≥ 4 wt% and $0.3\,\mathrm{L/m^2}$) on sand with silt (SM) and silty clay loam (CH) samples at velocities of 9 and 11 m/s and also reported effectivenesses $> 86\,\%$. 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 (0.4 up to 10 wt%) and application rates (1 to $3.5\,\mathrm{L/m^2}$) but 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 [110–114, 142]. Most of these studies also showed very high dust control effectivenesses $> 90\,\%$.

Hence, the resulting dust control effectiveness reported by different studies cannot simply be compared with each other and also does not enable to infer the potential performance of a dust suppressant at field conditions. However, the dust control effectiveness is a valuable parameter for comparing the performance 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 achieve similar performance.

3.4.2 Penetrometer Tests

Several studies performed penetrometer testing to investigate the penetration resistance of biopolymer-treated soils (e.g., [1, 109–114]). These studies demonstrated that the 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.

Effect of Biopolymer Type

On both tested soil types, all 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., Figure 3.8 and Figure 3.11). Thereby, the biopolymer type has a significant effect ($p < .001$) on the penetration resistance, with some biopolymers forming stronger crusts than others (Table 3.5 and Table 3.6). These trends are consistent with existing literature, showing that biopolymer-treated soils form crusts with different strengths depending on the biopolymer type (e.g., [1, 108, 110, 112]).

However, compared to results from existing literature (Table B.6), the penetration resistances measured in this study were mostly lower (Figure 3.8 and Figure 3.9). For instance, for soil samples treated with Acacia Gum, Lemboye et al. [110] reported penetration resistances between 10 and 145 N, for Sodium alginate between 7.5 and 25 N, and for Pectin between 15 and 39 N, respectively. While these penetration resistances are significantly higher than the results of the present study, Lemboye et al. [110] 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.

On fine-grained silica sand, the test results showed that the protein treatments (WP and FBPC) did not achieve as high penetration resistances as the polysaccharides (XG, CMC, and CS), which also applied to medium-grained sand samples treated with biopolymer concentrations < 0.75 wt%. WP treatments achieved the lowest penetration resistances on both tested soil types (Figure 3.8 and Figure 3.9). These trends are in agreement with a previous study by Sieger et al. [1], who also found that polysaccharide treatments tend to form stronger crusts than protein-treated samples. 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. By contrast, Toufigh and Ghassemi [112] reported that CMC treatments produce higher penetration resistances than XG. However, Toufigh and Ghassemi [112] likely performed their tests with a less potent XG than the present study, as they tested XG applications up to 1.5 wt% concentration without reporting difficulties regarding the viscosity. By contrast, the XG used in this study already yields highly viscous solutions that cannot be sprayed at concentrations > 0.75 wt%.

Effect of Concentration

On both tested soil types, penetrometer results showed that increasing the concentration significantly increased the penetration resistance of most tested biopolymers until reaching a plateau, beyond which the penetration resistance either stagnates or even slightly decreases (Figure 3.8, Figure 3.9, and Table 3.5). This trend is mostly consistent with findings from previous studies, which also observed that increasing the biopolymer concentration results in higher crust strength (e.g., [110, 113, 114]).

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 with a hand-held pocket penetrometer (calibrated spring), previous studies mainly tested higher application rates (1.3 to 3.5 L/m^2) and concentrations (0.3 to 10.0 wt%) and performed tests with precise laboratory penetrometers (loading machine mounted with penetrometer pin) [109–114]. 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 by the pocket penetrometer. By contrast, the high dosages tested by previous studies resulted in significantly stronger crusts

with more distinct differences in crust strength, precisely measurable by the stationary laboratory penetrometer.

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 (Figure 3.10, Figure 3.11). For both tested soil types, the two-way ANOVA also indicated that the application rate significantly affects the penetration resistance (Table 3.6). This trend is consistent with previous studies examining the effect of the application rate on the penetration resistance of biopolymer-treated soils [110, 111]. Thereby, the main difference is that previous studies revealed more distinct differences in penetration resistance than the present study. 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 [111]; 1.3 and 3.5 L/m^2 by [110]).

3.4.3 Correlation Between Penetration 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 3.2.3 and Table B.6. Furthermore, as found in the present and previous studies (Table B.6), 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.

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) on fine-grained silica ($r(106) = -.51$, $p < .001$) and medium-grained sand ($r(106) = -.81$, $p < .001$). Similarly, Toufigh and Ghassemi [112] and Ding et al. [109] also reported a strong correlation between 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 complementary to 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. [110], the penetration resistance, thus, allows 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 treatments with lower crust strength. For medium-grained sand, this implies that treatments with CS, XG, and partially FBPC likely exhibit a higher wind erosion resistance than WP treatments, whereas on 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.

3.4.4 Evaluation of the Potential of the Tested Polysaccharides and Proteins as Dust Suppressants at Mine Sites

Wind tunnel testing and pocket penetrometry are established methods for evaluating potential dust suppressants [1, 108, 112, 180]. Wind tunnel experiments performed by this study demonstrate that all 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 testing biopolymers [1, 109–114]. Therefore, it can be concluded that all tested biopolymer types show potential to be applied as dust suppressants, with polysaccharides proving to be more effective than proteins at lower concentrations.

While laboratory test results provided useful indications for suitable application parameters, true optimum application parameters can only be determined through iterative testing at field conditions. Thereby, effective application at field conditions will likely require higher dosages as environmental factors such as rainfall [110], UV radiation [117], and temperature fluctuations [213] 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, thus, require less frequent application [15, 54].

For potential large-scale applications, economic considerations are essential and must account for costs for biopolymer, water, equipment, fuel, personnel, and required rejuvenation intervals. The tested biopolymers are available at relatively low cost, with indicative bulk prices for XG = 2.0–3.0 USD/kg, CMC = ∼1.4 USD/kg, CS < 1.0 USD/kg, FBPC = 1.4–2.5 USD/kg, and WP = ∼1.4–2.5 USD/kg) [78, 85, 189–191], respectively. Thereby, polysaccharides (especially starches) are mostly cheaper than proteins. Equipment, fuel, and personnel are required to dissolve the biopolymers with an agitator in water and spray it on the soil by conventional water trucks or field sprayers with booms. Thereby, as water scarcity is increasing in various countries (e.g., Chile [214]), costs for 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 allow reducing water consumption.

Aside from cost-effectiveness-related considerations, environmental friendliness, biodegradability, availability, and ease of use constitute further relevant parameters for evaluating the dust suppressant potential of biopolymers. The biopolymers tested in this study are all biodegradable, and due to their frequent use in food and other industries, they are very well studied and characterised [78, 208, 209]. By contrast, commercially available dust suppressants can have adverse environmental effects, partially have proprietary formulations, or are studied insufficiently [14, 205]. 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) [91, 128], collagen (leather waste) [215, 216], and CMC (paper waste) [217]. 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 [69].

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 at real field conditions and raise awareness in the mining industry.

3.5 Conclusion

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/m²) 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 loss on medium-grained sand ranged from 1.09 to 423.9 g/m² (C = 2,645 g/m²), and on fine-grained silica sand from 0.3 to 225.5 g/m² (C = 26,177.4 g/m²), showing that all treatments significantly enhanced the wind erosion resistance relative to the control. Increasing the concentration reduced the soil loss until reaching a plateau concentration, and protein treatments achieved similar wind erosion resistances as polysaccharides but required higher concentrations.

2. In a second laboratory trial, biopolymers were applied at their respective plateau concentration and different application rates. On medium-grained sand, the soil loss ranged from 0.86 to 23.19 g/m² (C = 2,645 g/m²) and on fine-grained silica sand, from 0.62 to 10.67 g/m² (C = 26,177.4 g/m²), showing that all treatments achieved a very high dust control effectiveness regardless of the tested application rate. The reason for this is that the 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) on medium-grained sand and from 0.5 to 3.76 N(C < 0.5 N) on fine-grained silica sand. Thereby, the crust strength was significantly affected by the biopolymer type ($p < .001$) and increased significantly with higher concentrations ($p < .001$) and application rates ($p < .001$). In addition, the spearman rank correlation revealed a moderate to strong negative correlation between soil loss (g/m²) and penetration resistance (N) on fine-grained silica ($r(106) = -.51$, $p < .001$) and medium-grained sand ($r(106) = -.81$, $p < .001$). This implies that the pocket penetrometer can serve as an indirect indicator for evaluating the performance of potential dust suppressants.

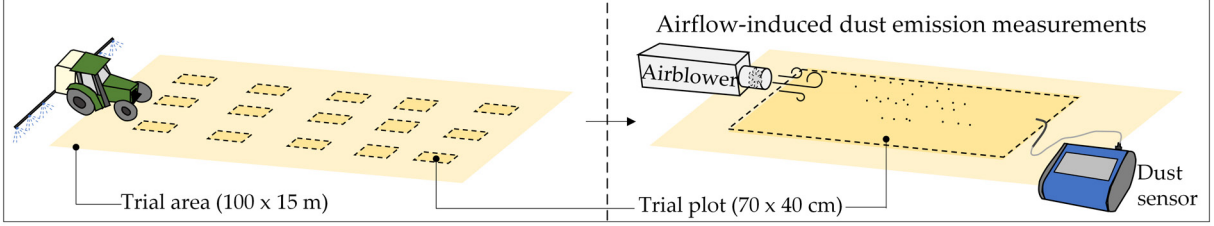
This study demonstrated that the tested polysaccharides and proteins have the potential to be applied as dust suppressants and facilitated the selection of application parameters suitable for first field trials.

Chapter 4

Article III: Large-Scale Field Trials

Effectiveness of Protein and Polysaccharide Biopolymers as Dust Suppressants on Mine Soils: Large-Scale Field Trials

Chapter 4: Article III: Large-Scale Field Trials			
Research Objective	Investigate the dust suppressant potential of selected biopolymer treatments in large-scale field trials on barren mine soils, analysing their effectiveness in suppressing airflow-induced dust emissions under real field conditions.		
Materials	Soils: • Medium-gr. sand (local mine soil)	Substances: • 3 biopolymers • 1 control (untr.)	Parameters: • 1 application rate • 1 concentration
Trial area preparation		Test methods	



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Authors: Johannes L. Sieger, Bernd G. Lottermoser, and Justus Freer
Keywords: field trials; wind erosion; dust control; dust suppressant; mine soils; biopolymer; polysaccharide; protein; dust concentration; corn starch; fava bean protein; xanthan gum
Citation: Sieger, J.L., Lottermoser, B.G., Freer, J. Effectiveness of protein and polysaccharide biopolymers as dust suppressants on mine soils: large-scale field trials. In: *Mining* 3.3 (2023), pp. 428–462, Doi: 10.3390/mining3030026. License: CC BY 4.0

4.1 Introduction

Dust emissions from active and abandoned mine sites have environmental, social, and economic impacts. They can affect local ecosystems [218, 219], the health of workers and local communities [5, 6, 13, 25, 33–35], may pose safety risks due to reduced visibility [120, 220], and can increase vehicle maintenance costs [120]. Furthermore, during strong wind events, dust can be transported and deposited on surrounding communities, causing a nuisance to residents. These mine dust emissions originate primarily from unpaved haul roads or large, exposed surfaces, such as tailings storage facilities, stockpiles, and overburden and waste dumps. They remain difficult to control due to their vast aerial extent and topographic exposition. During the operational phase of mines, revegetation of such areas is often not feasible from an operational perspective. The relevance of this issue will increase in the coming decades as both the extraction of raw materials and the frequency of droughts and strong wind events are predicted to increase [176, 177, 221].

The application of dust suppressants constitutes a proven method to mitigate emissions from exposed surfaces. However, many conventional dust suppressants, such as salt brines, petroleum-based products or synthetic polymers, are costly, can have adverse environmental effects [14], and the toxicity of (often proprietary) formulations is often insufficiently studied by independent third parties [15]. Furthermore, the ingredients of most synthetic polymers are still predominantly produced by the petrochemical industry from fossil fuels (oil and natural gas) [55]. Therefore, in order to progress towards more sustainable raw material extraction, there is a need for dust suppressants that are bio-based, environmentally friendly, readily available, and cost-effective. To address this need, recent research has focused on investigating the potential of biopolymers as dust suppressants (e.g., [110–112, 142]).

Biopolymers, such as starches and cellulose derivatives, are biodegradable and can be sourced from naturally abundant sources [78] or produced by microbial fermentation (e.g., xanthan gum) [208]. Dissolved in water, they can be sprayed on or mixed into the soil and act by agglomerating the soil particles, thereby increasing the wind erosion resistance of the soil. Recent laboratory studies have primarily analysed indicative parameters such as the penetration resistance [108–112, 142], crust thickness [64, 110, 111, 114], and moisture retention [94, 112–114, 116, 169] of biopolymer-treated soil samples or measured the wind erosion resistance in wind tunnel studies [110, 112, 113, 116, 118, 119, 142, 143]. While these laboratory studies have demonstrated the potential of biopolymers to act as dust suppressants, field trials are needed to investigate the effectiveness, durability, and scalability of their applications under actual field conditions. This need has recently also been articulated by Chang et al. [73] and Wade et al. [144].

In this study, large-scale field trials were conducted at the Inden open-cast lignite mine in Germany to evaluate the *effectiveness* (cf. Glossary, p. 129ff.) of three selected biopolymers - corn starch (CS), fava bean concentrate (FBPC), and xanthan gum (XG) - in reducing dust emissions from exposed, undisturbed mine soils. The field trials build on two previous laboratory studies by Sieger et al. [1, 2], which investigated the particle agglomeration potential and ability of selected biopolymers to enhance the soil wind erosion resistance. The field trials started with the large-scale application of biopolymers using a conventional field sprayer. Airflow-induced dust emissions were measured using a custom-built test setup and complemented by visual inspections of the plots tested and penetrometer testing. Acquired data were analysed in the context of meteorological data provided by a nearby weather station. Results of the presented field trials provide evidence that biopolymers can be used for effective short-term dust control on large, undisturbed mine soils.

4.2 Materials and Methods

4.2.1 Biopolymers

Previous studies by Sieger et al. [1] investigated the dust suppressant potential of 14 selected protein and polysaccharide biopolymers using penetrometer, moisture retention and crust thickness measurements. In a subsequent study, Sieger et al. [2] performed wind tunnel and penetrometer tests with 5 selected proteins and polysaccharides to investigate the wind erosion and penetration resistance of the biopolymer-treated soil samples at different application rates (L/m^2) and concentrations (%). Based on the results of these studies, suitable application parameters (see section 4.2.3) and three biopolymers were selected for this study:

- *Corn starch (CS).* Pre-gelatinised CS (type: CGel-Instant 12018) was obtained from Cargill B.V. (NL). According to the manufacturer's certificate of analysis, it has a moisture content of 5.8 wt%. The product primarily finds application as an instant thickener for puddings, sauces, soups, cakes, and bakery products.
- *Xanthan gum (XG).* Technical grade, readily dispersible XG (type: Xanthan TGRD) was obtained from Jungbunzlauer Austria AG (AT). It is a white, free-flowing powder, and according to the manufacturer's certificate of analysis, has a moisture content of 5.1 wt%.
- *Fava bean protein concentrate (FBPC).* Organic fava bean protein concentrate (60 % protein content) was obtained from Aljoa-Starkelsen (LV). It comes as a creamy light-yellowish powder and has a moisture content of 8.8 wt%.

4.2.2 Field Trial Location and Mine Soil

The field trials were performed on the upper bench of the overburden dump of the Inden open-cast lignite mine in North Rhine-Westphalia, 40 km west of Cologne, Germany (Figure 4.1a). Four trial areas were prepared, one for each biopolymer tested (CS, XG, and FBPC) and an untreated control (C) (Figure 4.1b). Each trial area measured 15 × 100 m and was marked with wooden stakes and flagging tape.

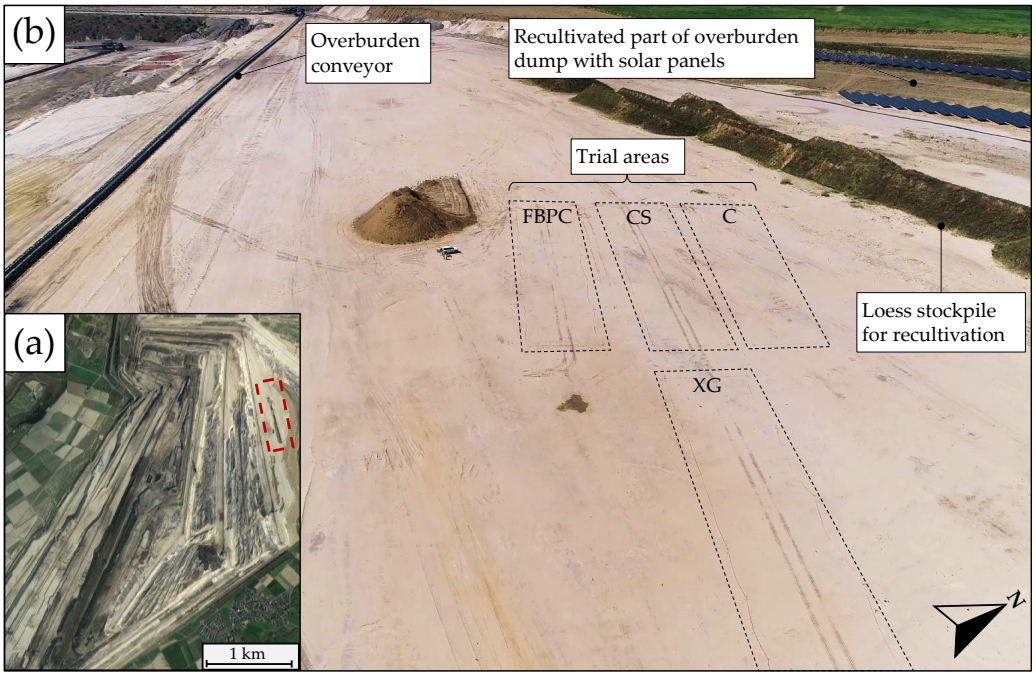

Figure 4.1: (**a**) Satellite image of the Inden lignite mine with the field trial location indicated by a dashed box. Adapted from Google Maps [222]. (**b**) Drone footage of field trial location, with trial areas indicated by dashed boxes (biopolymer-treated areas: FBPC, CS, and XG; untreated control: C.)

The particle size distribution was established for each trial area according to DIN EN ISO 17892-4 [181] (Figure 4.2 and Table 4.1) at the Unit of Mineral Processing, RWTH Aachen University. Each trial area was sampled at three locations, and samples were blended into representative composites. Based on the unified soil classification system (USCS), the material can be classified as medium- to fine-grained, poorly-graded sand (SP). All trial areas display similar particle size distributions, with the XG-treated area having a slightly coarser grain size distribution.

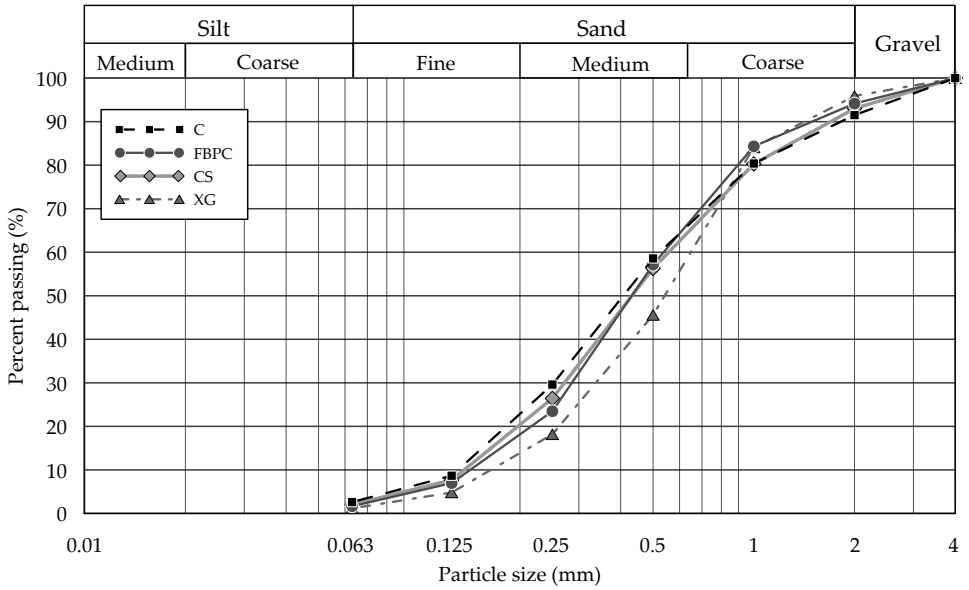

Figure 4.2: Particle size distribution of mine soils from different trial areas. C = control, CS = corn starch, FBPC = fava bean protein concentrate, XG = xanthan gum.

Substrate properties (i.e., geochemistry, mineralogy, specific gravity, pH, and soil colour, Tables 4.1 and 4.2) were established on a single composite sample generated by blending subsamples from all four trial areas. Geochemical composition of the composite sample was determined at ALS Geochemistry (Loughrea, Ireland), which performed whole-rock analysis using X-ray fluorescence spectroscopy (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) with four-acid digestion. Its mineralogy was established by semi-quantitative X-ray diffraction (XRD) using an AERIS benchtop XRD (Malvern Panalytical) instrument with a Co LFF tube (Institute of Mineral Resources Engineering, RWTH Aachen University, Aachen, Germany). Results demonstrate that the composite material consists primarily of quartz and orthoclase.

Table 4.1: Soil properties of biopolymer-treated (FBPC, CS, and XG) and untreated control (C) trial areas.

Parameter	Unit	Trial areas						Method
		C	FBPC	CS	XG	M	SD	
D_{60}	mm	0.52	0.54	0.56	0.64	0.57	0.05	DIN EN ISO 17892-4 [181]
D_{50}	mm	0.41	0.44	0.44	0.55	0.46	0.05	DIN EN ISO 17892-4 [181]
D_{30}	mm	0.25	0.29	0.28	0.33	0.29	0.03	DIN EN ISO 17892-4 [181]
D_{10}	mm	0.13	0.14	0.13	0.18	0.14	0.02	DIN EN ISO 17892-4 [181]
C_u	-	4.16	3.86	4.31	3.56	3.97	0.29	DIN EN ISO 17892-4 [181]
C_c	-	0.96	1.11	1.08	0.95	1.02	0.07	DIN EN ISO 17892-4 [181]
USCS	-	SP						ASTM D-2487 [182]
Specific gravity	g/cm³	2.66						DIN EN ISO 11508:2018-04 [183]
pH value		4.60						DIN EN 15933:2012-11 [184]
Soil colour	Munsell	1.3Y 6.5/1.7						

C_u = coefficient of uniformity, C_c = coefficient of curvature, USCS = Unified Soil Classification System, M = mean, and SD = standard deviation.

Table 4.2: Geochemistry of soil composite of all trial areas.

Oxides	Content (wt%)
SiO_2	95.44
Al_2O_3	2.17
K_2O	1.16
Fe_2O_3	0.18
TiO_2	0.10
Na_2O	0.07
SO_3	0.05
CaO	0.04
BaO	0.03
MgO	0.03
P_2O_5	0.02

4.2.3 Biopolymer Preparation and Application

The biopolymer concentrations for the treatments were based on a previous laboratory wind tunnel study conducted by Sieger et al. [2]. In that study, the authors determined the 'plateau concentrations' of selected biopolymers. These concentrations represent the point above which further increases have an insignificant impact on the treatments' effectiveness to reduce dust emissions. For the present study, the following plateau concentrations were selected: XG = 0.1 wt%, CS = 0.25 wt%, and FBPC = 0.75 wt%. For these concentrations, the results of the previous wind tunnel study suggest that all treatments will achieve a similar dust suppression performance [2]. In addition, the calculation of the required biopolymer mass accounted for the biopolymer's respective moisture content (section 4.2.1), and each biopolymer solution was applied to the trial areas at an application rate of 0.5 L/m². This resulted in treatment dosages of 0.7 g/m² for XG, 1.3 g/m² for CS, and 4.1 g/m² for FBPC.

A tractor-mounted field sprayer was used to prepare and apply the biopolymer solutions (Table 4.3 and Figure 4.3). The solutions were prepared by filling the tank of the field sprayer with the required volume of fresh water, adding the biopolymers via the external filling sluice, and mixing it with the field sprayer's built-in agitation system for 10 min until completely dissolved. Biopolymer solution of 750 L was required per test area. Constant pumping and spraying rates (L/min) throughout the spraying process were ensured by accounting for an additional 100 L solution in the tank, resulting in a total of 850 L solution prepared and 750 L applied.

Table 4.3: Field sprayer type and relevant application parameters.

Parameter	Value	Unit
Field sprayer model	Holder IS 1000	-
Tank volume	1000	L
Spraying width	15	m
Driving speed	1.1	km/h
Pump rate	69	L/min
Pump pressure	3.5	bar
Application rate per pass	0.25	L/m²
Nozzle size (ISO 10625)[223]	5	-
Nozzle count	18	-

The biopolymer solutions were applied to the trial areas with the tractor travelling longitudinally across the centre of the test area (Figure 4.3a). The total required application rate of 0.5 L/m² was achieved in two passes (0.25 L/m² per pass), with the tractor making a U-turn at the end of the first pass. After initial application on D0, no further reapplications were performed. With a

constant pump rate of 69 L/min and a spray width of 15 m, a constant driving speed of 1.1 km/h was required to achieve the 0.25 L/m² rate, which was maintained by the field sprayer's onboard control system. The spraying nozzles produced a fine mist, and no clogging, failure or other malfunction was observed throughout the spraying of any of the biopolymers (Figure 4.3b). The tank was emptied and rinsed between preparation of the different biopolymer solutions.

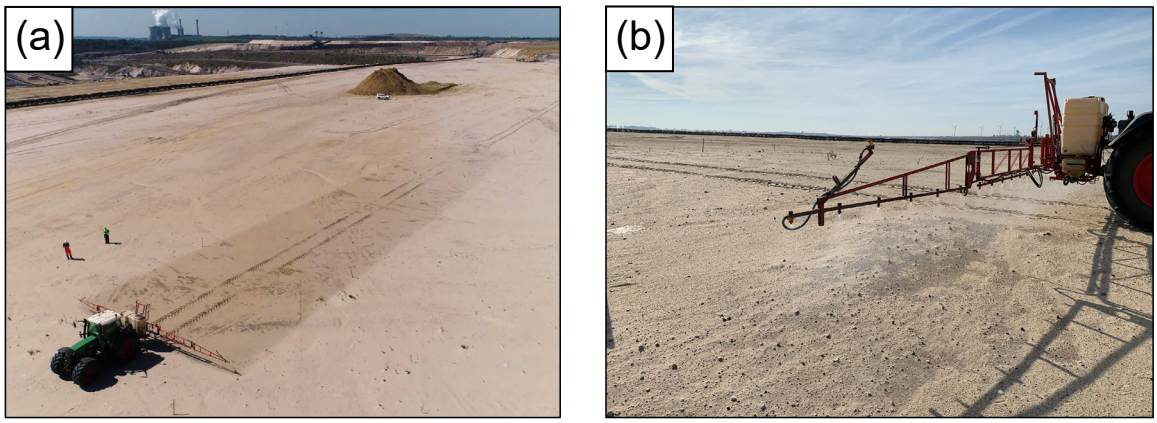

Figure 4.3: (**a**) Aerial picture of biopolymer application on trial areas. (**b**) Close-up shot of the field sprayer applying the biopolymer solution.

4.2.4 Test Methodology

The field trials started with biopolymer application on day 0 (D0, 08 August 2022) and continued until day 45 (D45, 22 September 2022). During this period, tests were performed on D2, D8, D15, D25, D32, D38, and D45. On each test day, the test programme consisted of:

1. measurements of dust emissions generated by exposing trial plots to a fan-generated airflow (section 4.2.5);
2. visual inspection of the trial plots tested in (1.); and
3. penetrometer tests (section 4.2.6)

Uniform testing across the trial areas was ensured by dividing the trial areas into separate sections for each test day (Figure 4.4). The right and left boundaries (each 15 m) were not measured and included in the test design in case adjustments to the field sprayer's travel speed and pumping rate were required at the start and end of the spraying process. A weather station located 3 km west of the field trial site provided meteorological data, including precipitation (L/m²), temperature (°C), relative humidity (%), and maximum wind speed (m/s).

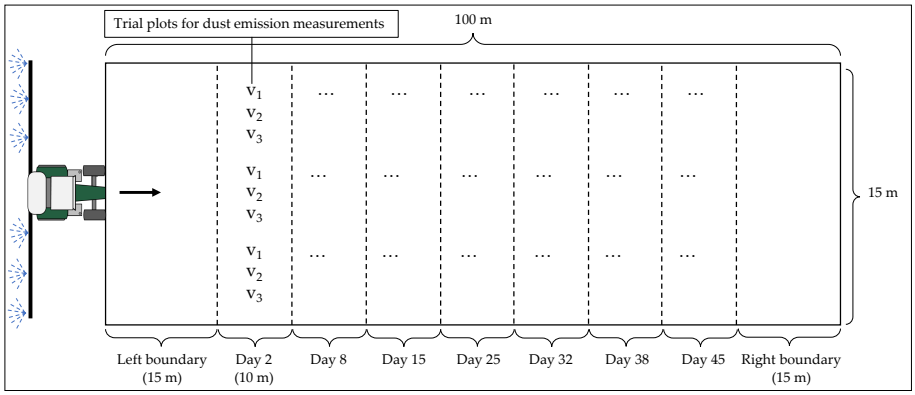

Figure 4.4: Schematic drawing of trial area with its subdivisions for the corresponding test days. Note. v_1, v_2, and v_3 denote indicative locations for the trial plots where dust emission measurements were performed (see section 4.2.5).

4.2.5 Dust Emission Measurements

On each test day, the effectiveness of the different biopolymer treatments was investigated by exposing representative 70 × 40 cm plots within the trial areas to different air speeds generated by an electric air blower and measuring the emitted dust emissions with an aerosol spectrometer (Figure 4.5). Each measurement lasted for 60 s, and a DustTrak 8533 aerosol spectrometer was used to measure particulate matter (PM) emissions of the $PM_{2.5}$ and PM_{10} fractions and total suspended particles (TSPs) in mg/m³. According to WHO guidelines, PM is a "mixture of solid and liquid particles in the air that are small enough not to settle out on the earth's surface under the influence of gravity, classified by aerodynamic diameter" [39]. The PM_{10} and $PM_{2.5}$ fractions represent the mass of soil particles contained in the TSPs, with an aerodynamic diameter ≤ 10 and $\leq 2.5\,\mu$m, respectively.

Figure 4.5: Test setup for dust emission measurements.

The DustTrak 8533 has a lower and upper detection limit of 0.001 and 150 mg/m³, respectively, and was set to a sampling rate of 1 Hz and a pump rate of 3 L/min. Prior to the field trials, the instrument was calibrated by the manufacturer to standard ISO 12103-1 [224], A1 test dust. Unbiased sampling was ensured using an isokinetic metal pitot tube with a 90 ° bend and a 2 mm inlet diameter. The pitot tube was mounted on a tripod 5 cm above the surface and 70 cm away from the electric air blower, facing the opposite direction of the air blow. The wind erosion resistance was investigated by performing tests at three different air velocities, namely, $v_1 = 13.3$ m/s (48 km/h), $v_2 = 15.5$ m/s (56 km/h), and $v_3 = 17{,}4$ m/s (63 km/h). These velocities represent different preset speed levels of the electric air blower. All tests were performed in triplicate ($n = 3$), and each was conducted on a new trial plot. Background emissions were determined on each test day. After measurements with substantial dust emissions, the aerosol spectrometer was recalibrated and the plastic hose and pitot tube were flushed with pressurised air from the inside. As previously pointed out by Freer et al. [62], such electric air blowers generate turbulent flow and are not directly comparable with portable wind tunnels that simulate the atmospheric flow causing natural wind erosion [225].

A custom-built wooden plate and a U-shaped frame provided reproducible test conditions (Figure 4.5). The DustTrak and the tripod were mounted to the wooden plate, and the sampling tube was connected to the DustTrak by a plastic hose. The wooden U-frame aligned the pitot tube,

trial plot, and fan for each measurement. The U-frame had inner dimensions of 40 × 100 cm and was mounted with a yellow 1 m tapeline. The electric air blower was deliberately positioned at 70 cm to the pitot tube, resulting in a 40 × 70 cm trial plot. In addition, the U-frame provided a reference for taking comparable pre- and post-test photographs. The electric air blower was stabilised and fixed by mounting it to a stainless-steel plate. A top-view picture of each trial plot was taken before and after each wind erosion test to visually compare the effect of the air velocities (v_1, v_2, and v_3) and the different trial areas among each other.

4.2.6 Penetrometer Tests

On each test day, a hand-held pocket penetrometer (H-4205) was used to measure the penetration resistance of the surface layers of the trial areas. Tests were performed with a 6.4 mm-diameter flat-ended penetrometer tip. The penetrometer has a load scale from 0 to 108 N and a resolution and lower reading limit of 0.5 N. Tests were performed up to a penetration depth of approximately 1 cm, with 20 replicates at an angle of 90 °.

4.3 Results

4.3.1 Meteorological Data

Figure 4.6 displays the precipitation (L/m²) measured by the local weather station throughout the field trial period, with the day of application and the different test days (T#1–T#7) indicated by black squares. Further meteorological data, including temperature, humidity, and maximum wind velocity, are appended in Table C.1, p. 117. The first small precipitation event of 0.4 L/m² occurred on the seventh day (D7) after biopolymer application, one day before T#2. Further rainfall of 4.3 L/m² was recorded between T#2 and T#3. Two days before D25 (T#4), the first large precipitation event, 6.8 L/m², took place. The following week, significant rainfall of 31.4 L/m² occurred from D29 to D31 before T#5 (D32). Ahead of T#6, again, considerable rainfall of 11.5 L/m² fell between D36 and D38. The subsequent days were also characterised by further rainfall, followed by only slight precipitation of 0.2 L/m² on D42 and D43 and no rainfall on D44 and D45 (T#7).

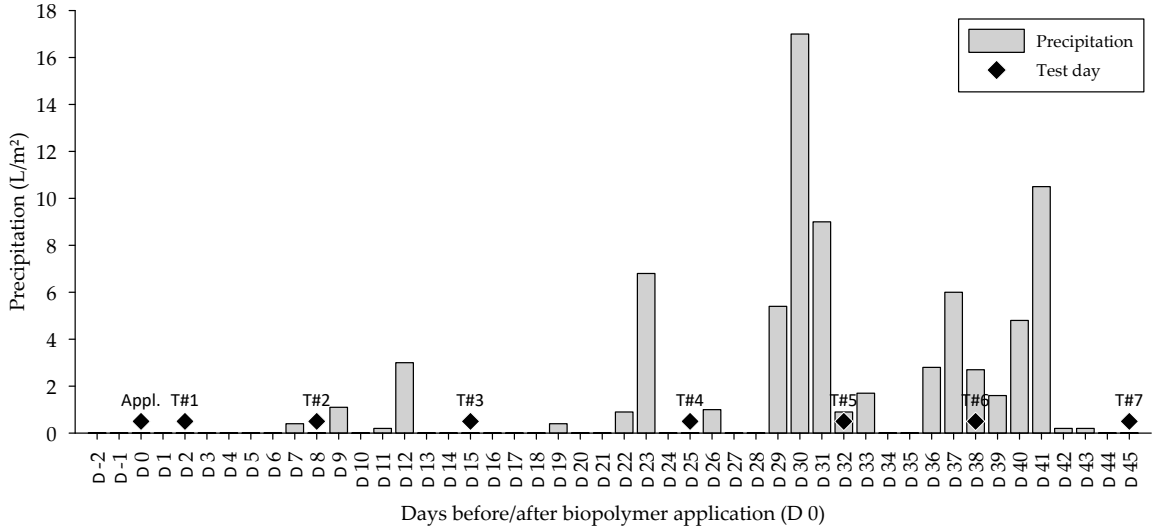

Figure 4.6: Precipitation during the field trials, starting two days before biopolymer application (D−2, 06 August 2022) and lasting until day 45 (D45, 22 September 2022). Note. the numerical values are appended in Table C.1, p. 117. Appl. = date of applying biopolymers.

4.3.2 Dust Emission Measurements

Time Series of Individual Measurements

Figure 4.7 shows the time series of the TSP concentrations measured during the dust emission tests performed on D2 at air speeds of v_1, v_2, and v_3. Irrespective of the velocities tested, the control group (C) showed significant mean TSP emissions (at $v_1 = 49.1\,\mathrm{mg/m^3}$, $v_2 = 36.08\,\mathrm{mg/m^3}$, and $v_3 = 28.04\,\mathrm{mg/m^3}$), while all biopolymer-treated plots exhibited considerably lower emissions ranging between 0.05 and 0.43 $\mathrm{mg/m^3}$. The measured emissions typically peaked in the first 3 to 10 s, whereafter they gradually decreased, a trend that generally applied to all tests throughout the field trials. On D2 and a few other test days, emissions from the untreated control reached the DustTrak's upper detection limit of 150 $\mathrm{mg/m^3}$ for several seconds when exposed to air velocities v_2 and v_3. It is assumed that the actual emissions during these events were above the detection limit. As shown in Figure 4.7, emissions tended to reduce more rapidly at higher air velocities (e.g., v_2 and v_3 on the untreated control).

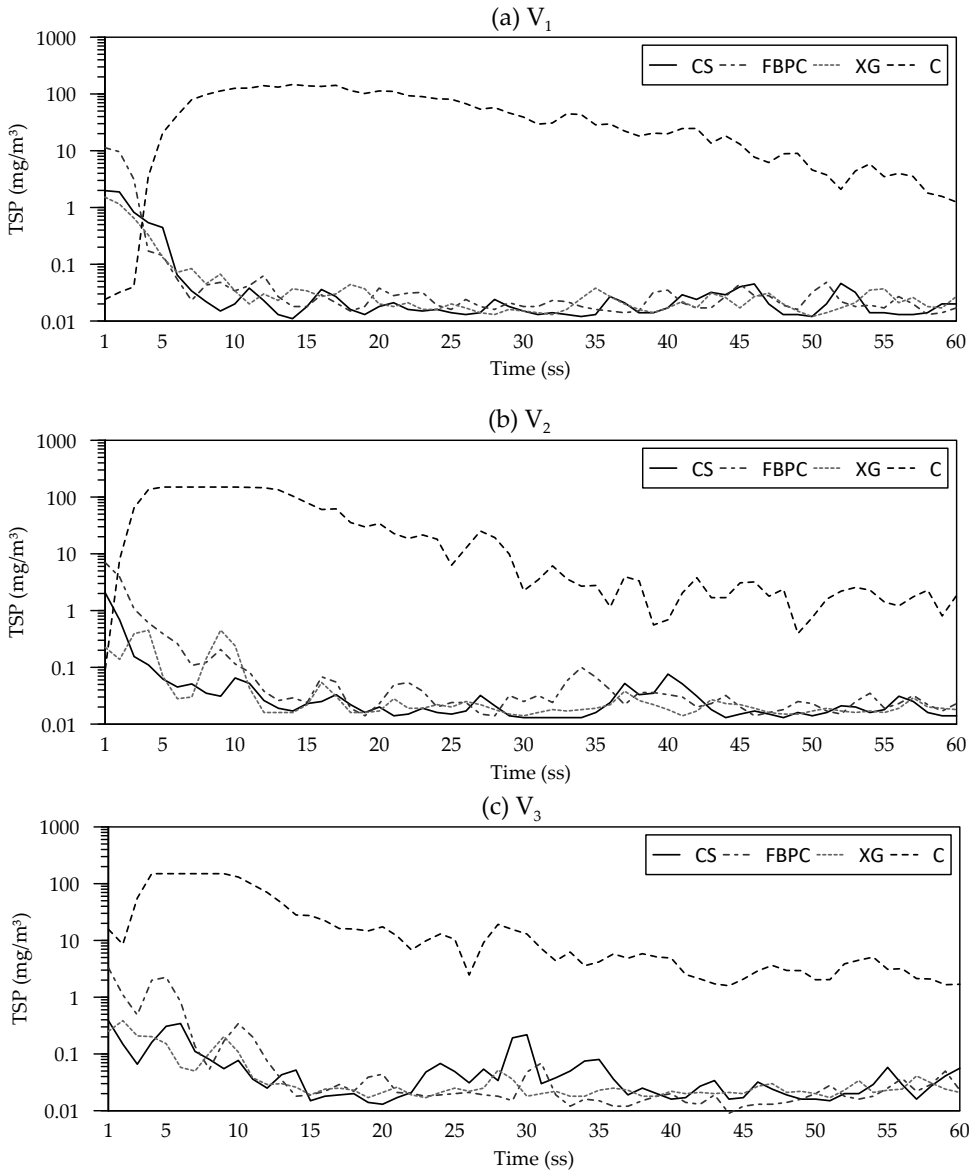

Figure 4.7: Time series of TSP emissions measured on the first test day (T#1) two days after the biopolymer solution was applied (D2). Tested wind velocities: (**a**) $v_1 = 13.3\,\mathrm{m/s}$, (**b**) $v_2 = 15.5\,\mathrm{m/s}$, and (**c**) $v_3 = 17.4\,\mathrm{m/s}$.

Temporal Development Throughout the Field Trials

Figure 4.8 shows the results of the (a) TSPs, (b) PM_{10}, and (c) $PM_{2.5}$ emissions measured on trial plots exposed to $v_1 = 13.3\,\mathrm{m/s}$. The corresponding results for dust emission measurements performed at $v_2 = 15.5\,\mathrm{m/s}$ and $v_3 = 17.4\,\mathrm{m/s}$ are displayed in Figures 4.9 and 4.10. The dust emissions measured on the untreated and biopolymer-treated trial plots varied significantly throughout the field trials. In contrast, the recorded background load remained consistently low, with TSPs ranging from 0.02 to 0.05 $\mathrm{mg/m^3}$. The results from the trial plots exposed to air speeds of v_1, v_2 and v_3 show similar overall trends. The following paragraphs describe the temporal development of the dust emissions measured throughout the field trials for plots exposed to air flows at v_1.

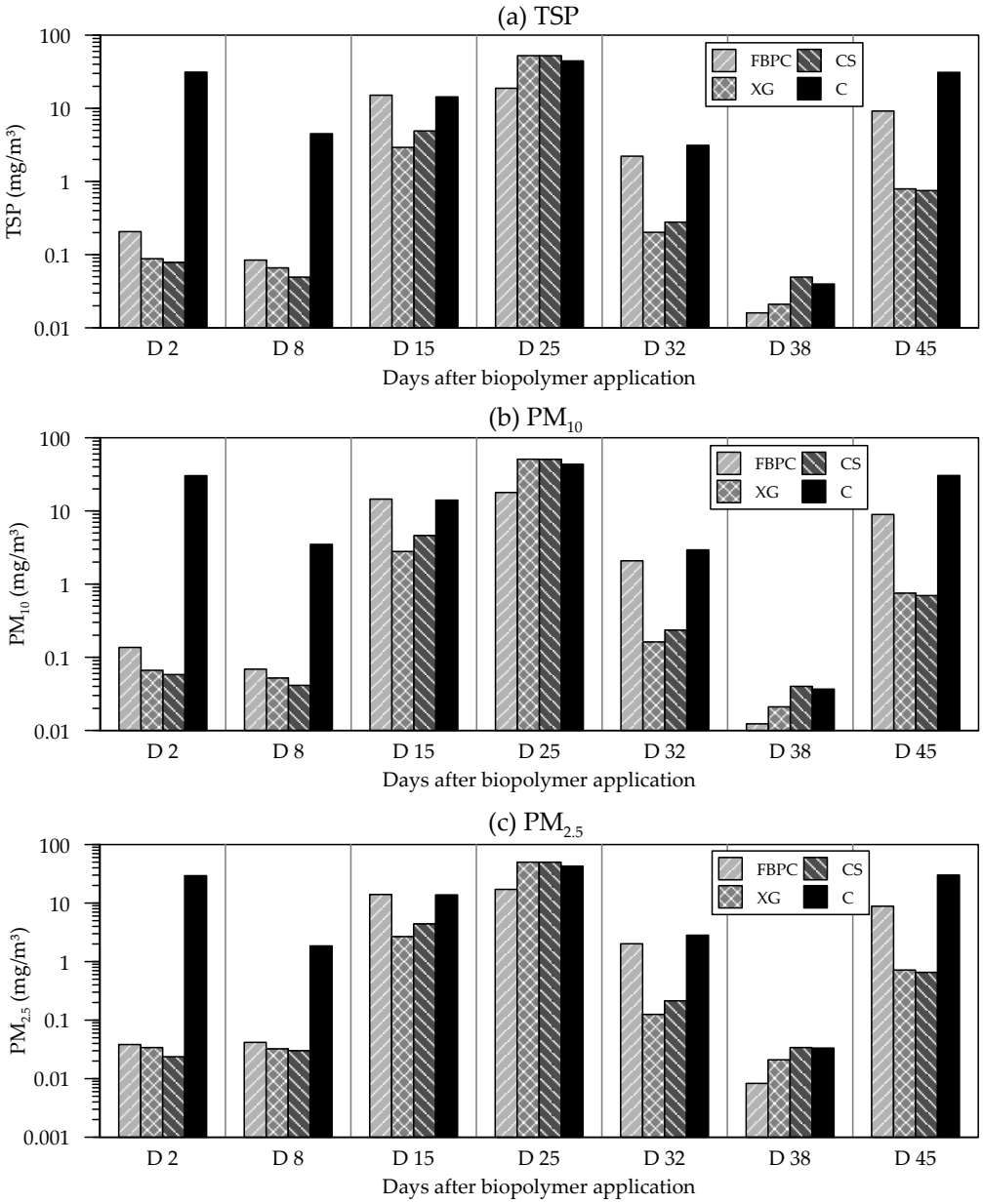

Figure 4.8: Mean dust emissions measured on untreated control (C) and biopolymer-treated trial plots exposed to air speed of $v_1 = 13.3\,\mathrm{m/s}$. (a) TSPs, (b) PM_{10}, (c) $PM_{2.5}$. Biopolymer treatments were applied at $0.5\,\mathrm{L/m^2}$ and concentrations for FBPC = 0.75 wt%, CS = 0.25 wt% , and XG = 0.13 wt%. Tests were performed in triplicate ($n = 3$), and numerical data of the test results, including mean (M) and standard deviation (SD), are appended in Table C.2, p. 119.

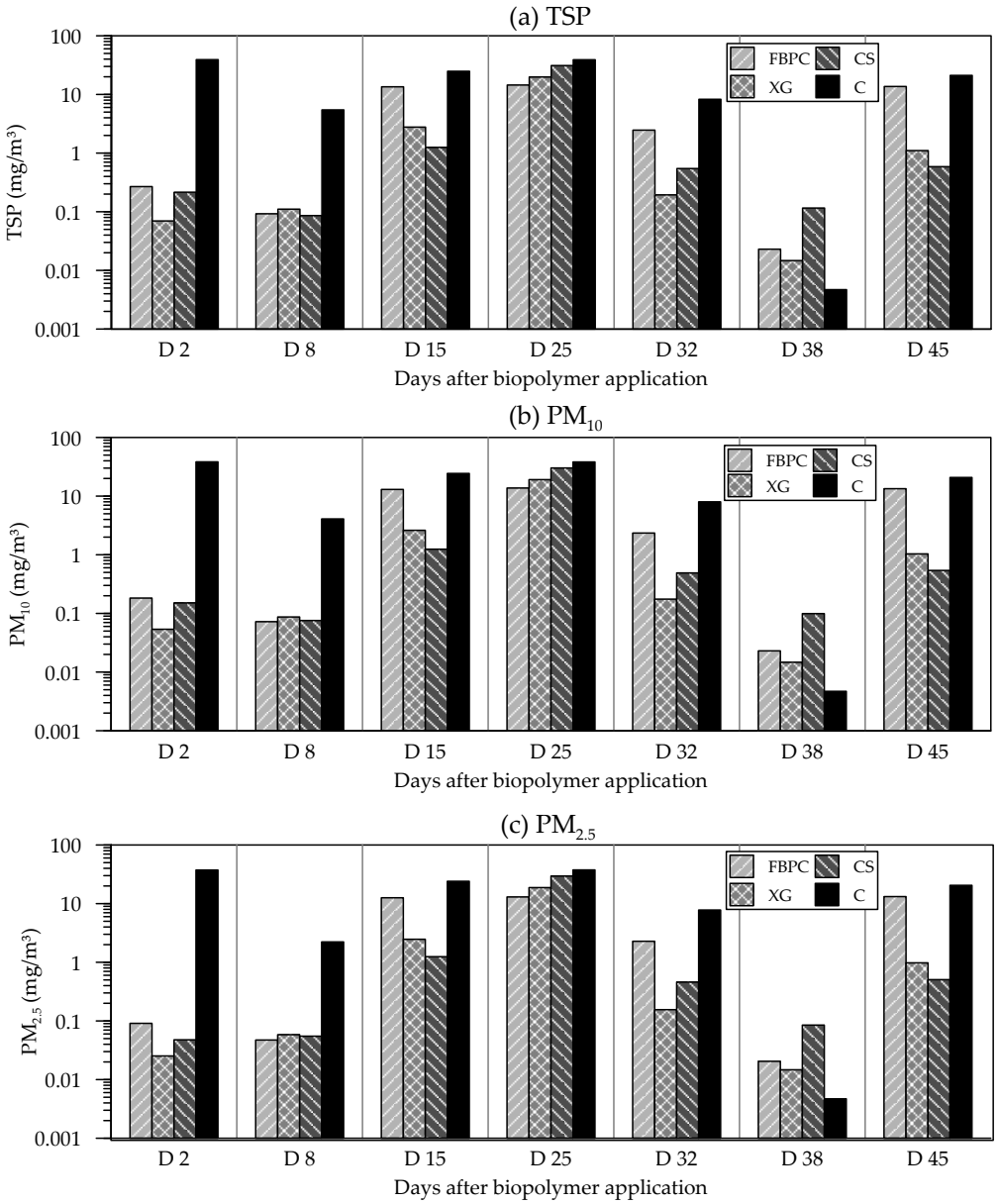

Figure 4.9: Mean dust emissions measured on untreated control (C) and biopolymer-treated trial plots exposed to air speed of $v_2 = 15.5\,\mathrm{m/s}$. (a) TSPs, (b) PM_{10}, (c) $PM_{2.5}$. Tests were performed in triplicate ($n = 3$), and numerical data of the test results, including mean (M) and standard deviation (SD), are appended in Table C.3, p. 120.

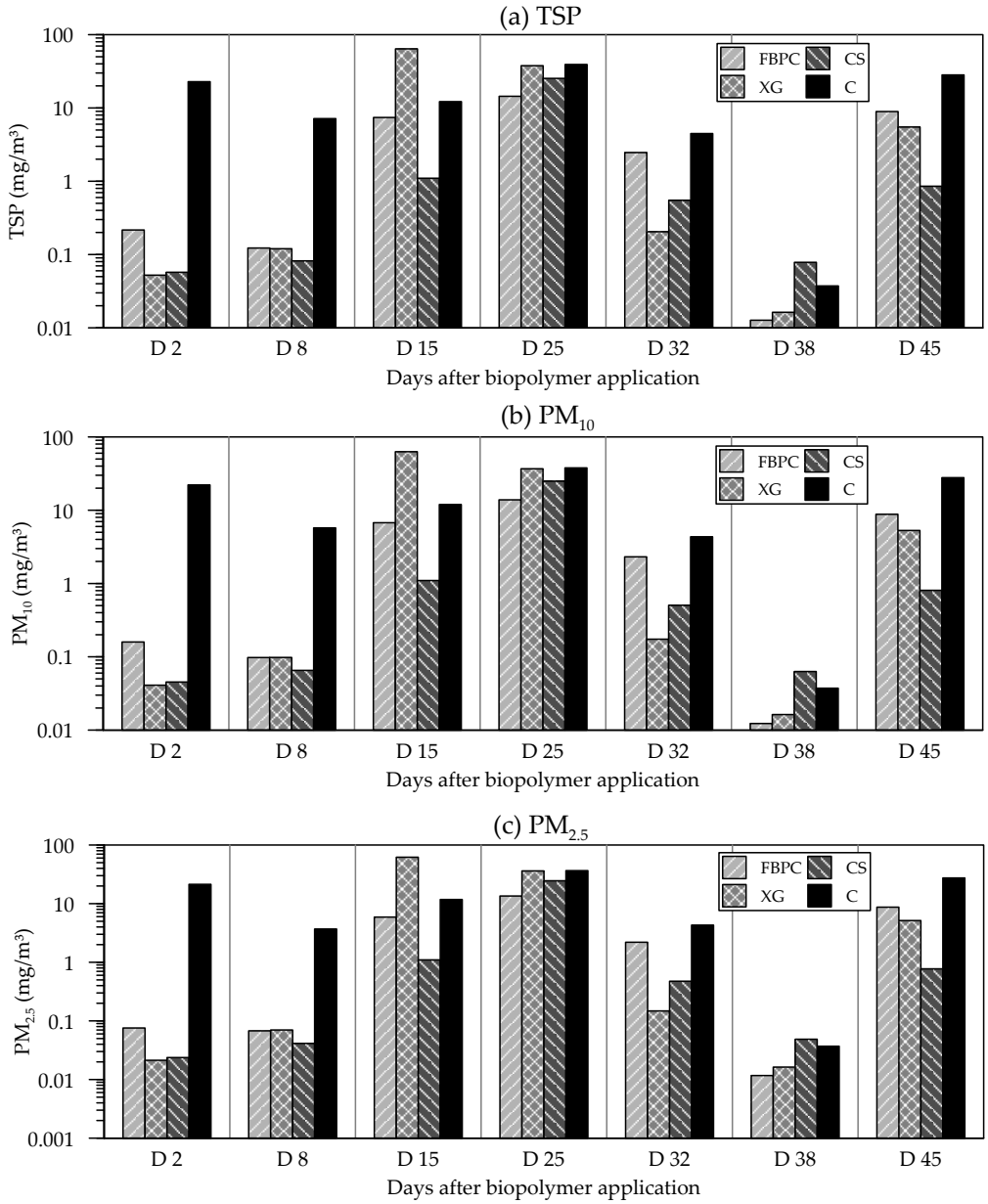

Figure 4.10: Mean dust emissions measured on untreated control (C) and biopolymer-treated trial plots exposed to air speed of $v_3 = 17.4\,\mathrm{m/s}$. (a) TSPs, (b) PM_{10}, (c) $PM_{2.5}$. Tests were performed in triplicate ($n = 3$), and numerical data of the test results, including mean (M) and standard deviation (SD), are appended in Table C.4, p. 121.

Temporal development of dust emissions of trial plots exposed to v_1 (see Figure 4.8):

- *D2 and D8.* Here, the biopolymer-treated trial plots (CS, FBPC, and XG) exhibited low dust emissions, while significant emissions were measured on the untreated plots. Mean TSP emissions of the biopolymer-treated plots ranged from 0.05 to 0.12 mg/m³, while emissions from the control section (C) ranged from 4.5 to 31.2 mg/m³. Among the biopolymer treatments, the FBPC-amended test sections exhibited slightly higher emissions than the XG- and CS-amended ones.
- *D15 and D25.* Compared to the first two test days, the results of D15 and D25 showed different behaviour, as dust emissions gradually increased across all trial plots. On D15, the observed TSP emissions from the biopolymer-treated plots increased notably (CS = 4.9 mg/m³, FBPC = 15.1 mg/m³, and XG = 2.9 mg/m³), with the FBPC-amended plots displaying simi-

lar emissions to the control (C = 14.3 mg/m³). The peak emissions of the study were recorded on D25, whereby the FBPC-treated plots exhibited lower TSP emissions (18.8 mg/m³) than the other plots (CS = 52.4 mg/m³, XG = 52.5 mg/m³, C = 44.5 mg/m³).
- *D32 and D38.* On D32 and D38, the measured emissions decreased, reaching the field trial's low point on D38. Compared to D25, all trial plots exhibited relatively low TSP emissions on D32 (CS = 0.3 mg/m³, XG = 0.2 mg/m³, FBPC = 2.2 mg/m³, and C = 0.1 mg/m³). On D38, emissions decreased even further, with only marginal TSP emissions measurable on all plots (CS = 0.05 mg/m³, FBPC = 0.02 mg/m³, XG = 0.02 mg/m³, and C = 0.03 mg/m³).
- *D45.* On the last test day, the measured emissions had increased considerably compared to D38 (CS = 0.75 mg/m³, FBPC = 9.18 mg/m³, XG = 0.79 mg/m³, and C = 31.0 mg/m³). Therefore, the control exhibited the highest emissions.

Comparison of TSP emissions between the trial plots exposed to v_1, v_2, and v_3:

- *Overall behaviour*: Dust emissions of tests performed at v_2 and v_3 display a similar temporal development to that previously described for v_1. Again, tests on D2 and D8 showed low emissions on the biopolymer-treated plots and high emissions on the untreated plots, followed by dust emissions increasing on D15 and peaking on D25. After that, emissions decreased on D32, bottomed out on D38, and increased again on D45.
- *Comparison of v_1 with v_2 and v_3*: On D2 and D8, the average emissions induced by air speed of v_2 mostly increased slightly compared to v_1, while increasing the velocity to v_3 mostly resulted in a decrease compared to v_2. By contrast, on D15 and D25, the TSP emissions at v_2 on the biopolymer-treated plots were mostly lower than at v_1. Notably, on D15, the XG-treated plots subjected to v_3 showed considerably higher emissions than the other tested fields. On D32, emissions decreased on all the plots tested and bottomed out on D38, irrespective of the velocity tested. Lastly, on D45, the CS- and XG-treated plots exposed to v_2 displayed similar emissions as v_1, whereas emissions measured for FBPC-treated plots were increased.
- *Conclusion:* A comparison of the results for the different velocities did not reveal a clear trend regarding the effect of air speed on the measured dust emissions.

Share of PM_{10} and $PM_{2.5}$ Fractions

Throughout the field trials, PM_{10} and $PM_{2.5}$ emissions followed a similar temporal development to that described for TSPs. PM_{10} emissions accounted for 89 % ($SD = 9$) of the TSP emissions measured on plots exposed to v_1. In addition, 76 % ($SD = 24$) of the recorded TSP emissions were associated with the $PM_{2.5}$ fraction. The percentage allocation of the TSP emissions to the PM_{10} and $PM_{2.5}$ emissions was similar for the tests carried out at v_2 and v_3. This implies that most of the measured emissions belong to the $PM_{2.5}$ fraction.

Conclusions

Irrespective of the velocity tested, all biopolymer-treated trial plots showed significantly reduced dust emissions on D2 and D8, while the untreated plots exhibited significant emissions. On the subsequent test days, all trial plots showed a similar overall development. The control (C) showed the highest emissions on almost all test days and was only matched by the FBPC-treated plots on D15 and D32 and the CS- and XG-amended plots on D25. A direct comparison of the biopolymer amendments revealed that the XG-and CS-treated plots showed similar emission behaviour, mainly exhibiting lower emissions than the FBPC-treated plots (i.e., on D2, D8, D15, D32, and D45). Most of the TSP emissions were attributed to the $PM_{2.5}$ fraction. Finally, although the measured dust emissions differed for the velocities tested, no clear trend could be identified regarding the effect of the velocity on the measured dust emissions.

4.3.3 Visual Inspection of Trial Plots

While closer inspection of the biopolymer-treated trial areas revealed that the sand particles agglomerated to a surficial crust, it was impossible to take intact crust samples or perform crust thickness measurements, as the formed crusts were too fragile and brittle. Figures 4.11 and 4.12 show representative photographs of the trial plots taken after the dust emission measurements at $v_1 = 13.3\,\mathrm{m/s}$. Corresponding photographs of the trial plots subjected to v_2 and v_3 are appended in Figures C.1-C.4 (p. 122-125). The following paragraphs describe the visual characteristics that can be discerned from the photographs. In general, most of the visually detectable wind erosion occurred during the first few seconds of each test. Saltation appears to be the dominant erosion mechanism, with particles close to the electric fan being eroded by air and their saltation causing further erosion down the line of airflow. The higher the velocity tested, the faster the erosion process.

- *Untreated trial plots (C).* The fan-generated air flow caused significant erosion on the untreated trial plots, resulting in distinct cone-shaped wind erosion traces on each testing day. The widths and lengths of the erosion traces slightly varied throughout the test days, with less erosion being perceived on D8 and D38 (for v_1). On D32, the erosion traces resulting from tests at v_2 and v_3 were slightly bent due to crosswinds. The dimensions of the erosion traces increased significantly with the higher velocities tested (Figures C.1 and C.3).
- *FBPC-treated trial plots.* On D2, only a few sand particles were eroded by the induced airflow, regardless of the velocity tested, whereas tests on D8 produced visually perceivable erosion marks. From D15 onwards, the typical cone-shaped erosion traces became visible, becoming larger and more distinct with each measurement day. However, throughout the field trials, the erosion traces on the FBPC-treated soil (v_1) were smaller than the corresponding traces on the untreated plots. In contrast, the v_2 and v_3 trials resulted in more similar erosion traces.
- *CS-treated trial plots.* Similarly to the FBPC-treated plots, almost no erosion traces were observed after the tests on D2 and D8, regardless of the velocity tested. On D15, the induced airflow produced clearly visible erosion traces, but not as distinct or large as the corresponding untreated plots (for v_1, v_2, and v_3). From D25 onwards, the CS-treated plots exhibited erosion traces of similar shape and size to the untreated plots at all velocities tested.
- *XG-treated trial plots.* Similarly to the CS- and FBPC-treated trial plots, the XG-treated plots showed almost no wind erosion throughout the tests on D2 and D8 at all velocities. However, on D8, the XG-treated plots displayed slightly larger erosion traces than the CS- and FBPC-treated plots. From D15 onwards, the conical erosion traces could be observed at all velocities tested, and their size increased with each test day. However, the traces were not as distinct or large as the corresponding untreated trial plots.

Conclusion. Regardless of the velocity tested, all biopolymer-treated trial plots showed only marginal erosion on D2 and D8, whereas the control showed substantial erosion. From D15 onwards, the biopolymer-treated trial plots also began exhibiting cone-shaped erosion traces similar to those of untreated plots. However, until the end of the field trials, these traces were mainly smaller and less distinct. The lengths and widths of the cone-shaped erosion traces increased with higher air velocities tested.

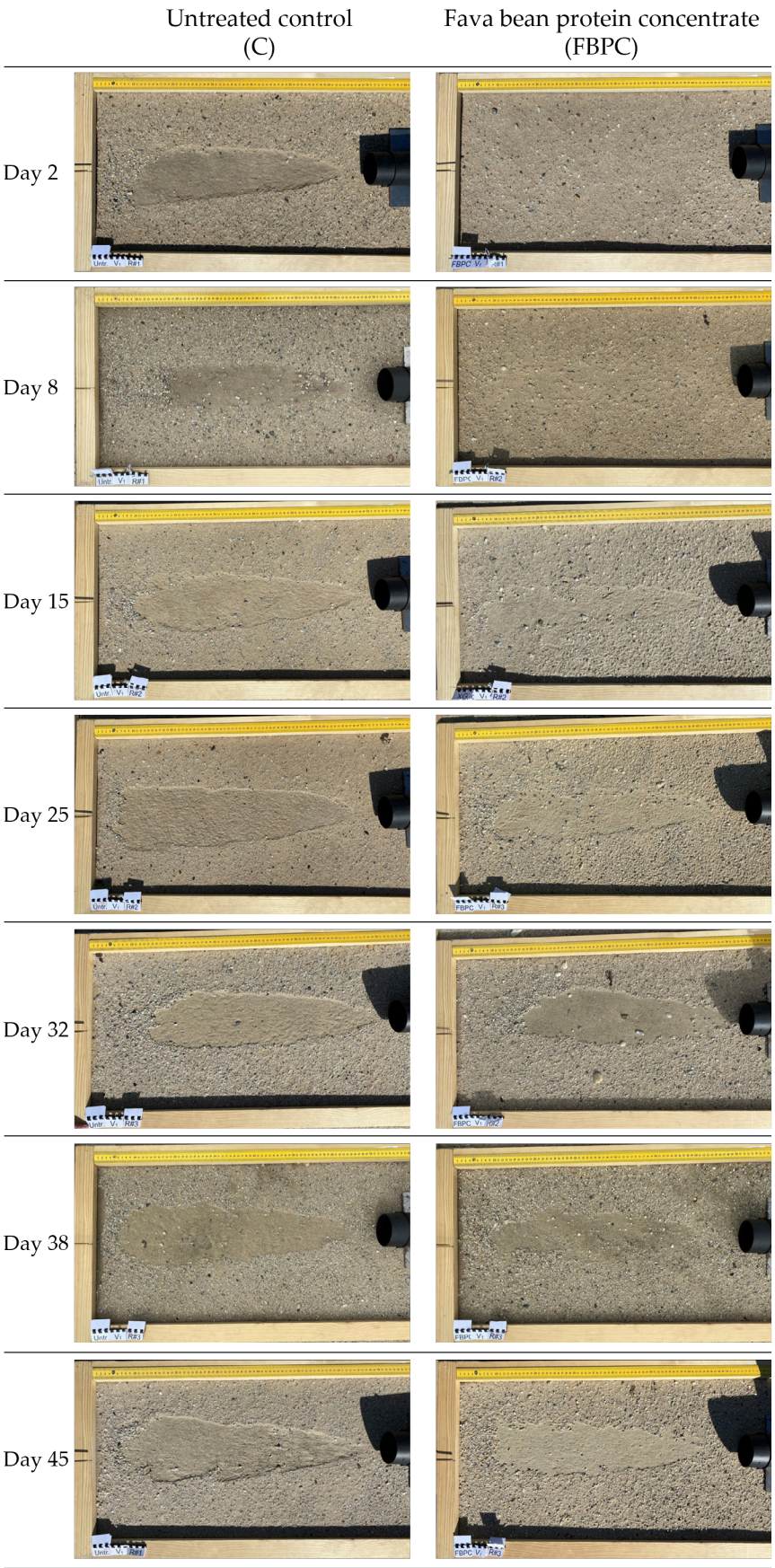

Figure 4.11: Exemplary photographs of plots on the untreated and FBPC-treated trial areas after subjecting them to air speed of v_1 (13.3 m/s) for 60 s. The trial plots had dimensions of 40×70 cm.

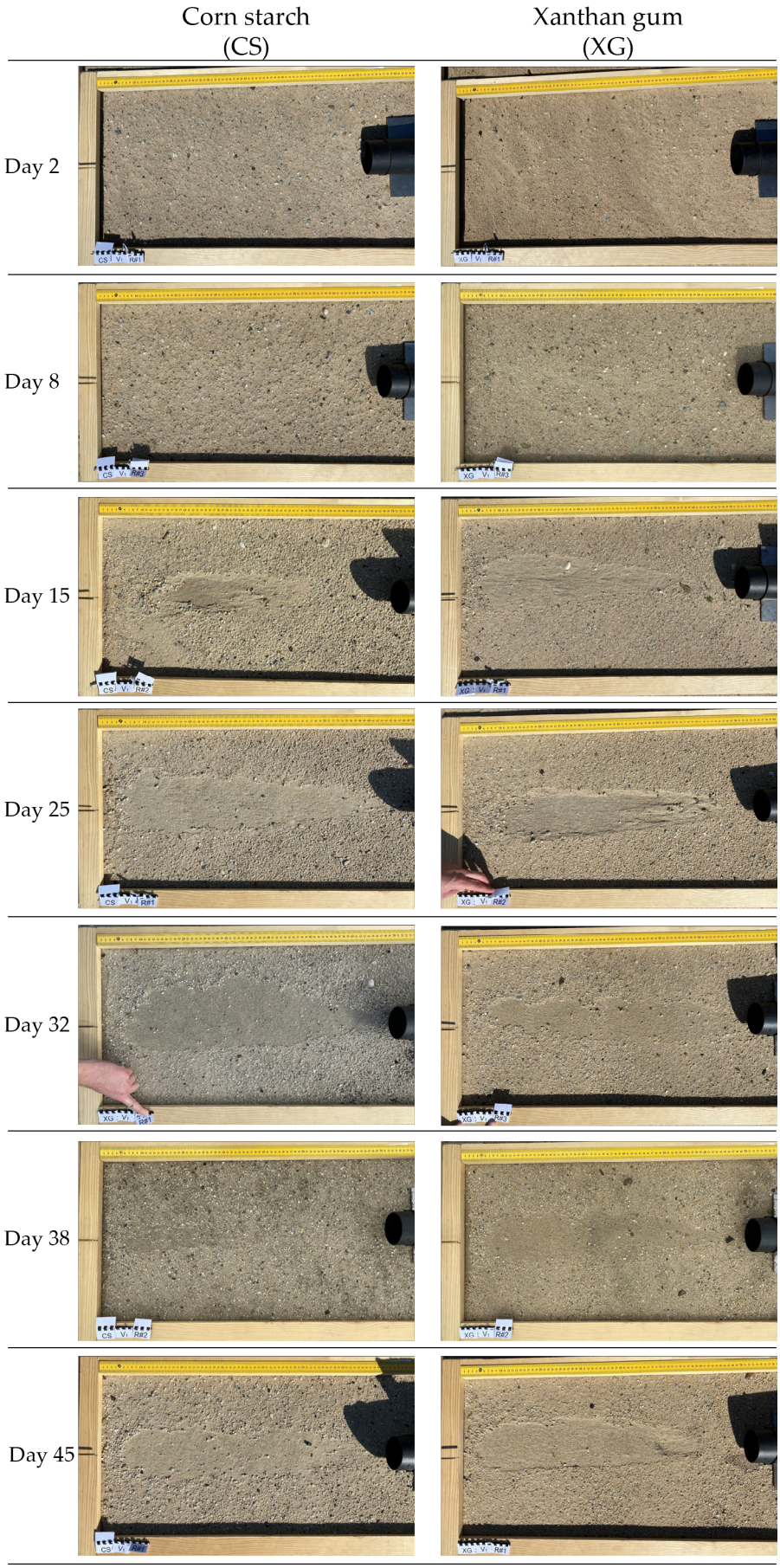

Figure 4.12: Exemplary photographs of CS- and XG-treated trial plots after subjecting them to air speed of v_1 (13.3 m/s) for 60 s. The trial plots had dimensions of 40×70 cm.

4.3.4 Penetration Resistance

Figure 4.13 shows the results of the pocket penetrometer tests performed on the trial areas. The top 1 mm of the sand was typically relatively loose on most test days and trial areas, with the penetration resistance increasing below this point. Throughout the field trials, the untreated trial areas exhibited relatively low penetration resistance ranging from 3.2 to 3.6 N on D2, D8, and D15, and increased slightly from D25 onwards. By contrast, the biopolymer-treated trial areas displayed increased penetration resistance on D2 and D8, ranging from 6.7 to 20.3 N, which decreased significantly from D15 onwards. The CS-treated trial areas displayed the highest penetration resistance until D8. After that, it dropped to a level similar to the untreated area. The FBPC-treated area showed high resistance until D8 (18.8 N) and halved to 9.8 N on D15. However, it still exhibited the highest resistance until D38 (8.2 N), reaching a similar level as the other trial areas (D38: XG = 5.4, CS = 7.3, and C = 6.7 N). The XG-treated trial areas showed elevated resistance that gradually decreased until D15. From there on, it exhibited a similar trend as the untreated area. In general, the penetration resistance on all areas exhibited relatively high variability, as reflected in the standard deviations of the test results (Table C.5, p. 126).

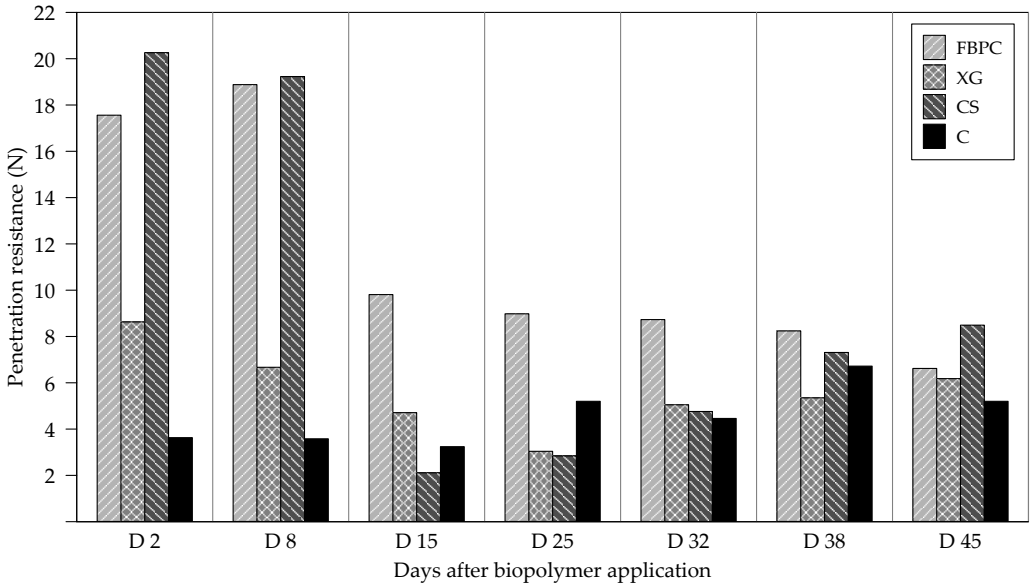

Figure 4.13: Mean penetration resistance of untreated control (C) and biopolymer-treated trial areas. Biopolymer treatments were applied at 0.5 L/m² and concentrations for FBPC = 0.75 wt%, CS = 0.25 wt%, and XG = 0.13 wt%. Tests were performed with replicates ($n = 20$), and numerical data of the test results, including mean (M) and standard deviation (SD), are appended in Table C.5, p. 126.

4.4 Discussion

4.4.1 Findings from Previous Field Trials

Several previous field trials have examined the application of dust suppressants. Some have investigated their application on unpaved roads, where traffic-related mechanical disturbance is the primary source of dust emissions (e.g., [58, 59, 119, 120, 210, 226, 227]). Others have tested their application on barren, undisturbed areas where wind erosion is the main source of dust emissions (e.g., [121, 140, 167, 228]). As the present field trials investigated the dust emissions from undisturbed, biopolymer-treated areas exposed to airflow, this discussion focuses on the latter. In the following, the main results of previous field trials are summarised, and their key parameters and findings have additionally been compiled in Table C.6, p. 127.

Previous field trials by Park et al. [140], Freer et al. [62], and Shen et al. [167] tested diverse substances and application parameters on different soil types and areas. They found that the treatments allowed effective short-term suppression of dust emissions (Table C.6). Park et al. [140] applied poloxamer (amphiphilic copolymer) on tailings storage facility slopes and beaches, reporting significantly reduced PM_{10} emissions one week after application, but almost no residual effect in the second week. Freer et al. [62] tested different food-processing by-products and reported considerable short-term emission reductions up to 14 days after application. Shen et al. [167] reported an efficacy of over one month when testing a starch-polyacrylamide mixture on loess soil. All these studies attributed the degradation of the treatments' effectiveness to rainfall, leaching the substances from the soil surface.

In contrast to these treatments with relatively short-term effectiveness, the highest durability of a treatment was reported by Kavouras et al. [228], who tested tall oil pitch on sandy loam and reported significantly reduced PM_{10} emissions over 3 to 6 months. The high durability of the treatment was probably due to the high dosage tested (concentration: 14 to 17 % and application rate: 2 L/m^2) and the fact that tall oil has a higher water resistance than other organic treatments [48]. Contrary to the results reported in these previous studies, only Preston et al. [121] observed no clear effect in their field trials with different dust suppressants on tailings soils and attributed this mainly to the field conditions (especially precipitation).

Further in-depth analysis of the field trials in terms of how the effectiveness and durability of a treatment are affected by parameters, such as the suppressant type, application rate, and concentration, is limited due to differences in the trials' test conditions and methods (e.g., soil properties, weather, and test method). The fact that the field trial results are not simply comparable underlines the value and need for repeated field trials to determine suitable suppressant types and application parameters for a given soil type and location. As a direct comparison of data from the documented field trials and those of other studies is impossible, the following discussion focuses primarily on interpreting the results of the present field trials.

4.4.2 Interpretation of Field Trial Results

Dust Emissions

The results of the field trials were analysed by cross-referencing the measured airflow-induced dust emissions (section 4.3.2) with the precipitation data (section 4.3.1), the visual inspection observations (section 4.3.3), and the penetrometer test data (section 4.3.4), and are presented in the following paragraphs. The interpretation focuses primarily on the main trends observed, as a more detailed comparison of the absolute test results is limited by the naturally inherent heterogeneity (e.g., moisture, particle size, and compaction) of the trial areas, spanning 6000 m^2.

D2 and D8. At the start of the field trials, the biopolymer treatments were applied in dry field conditions (D0), with no rainfall recorded until the first test day (D2) and only marginal rainfall one day before the second test day (D8). During the dust emission measurements on D2 and D8, the biopolymer-treated trial plots (FBPC, XG, and CS) exhibited only marginal dust emissions, regardless of the air velocity tested (v_1, v_2, and v_3). In contrast, the untreated plots (C) showed significant emissions. These results are consistent with the visual observations, which showed marginal erosion traces on the biopolymer-treated plots, while untreated plots displayed substantial cone-shaped traces (Figures 4.11, 4.12 and C.1-C.4). Thus, all the biopolymer treatments tested significantly increased the wind erosion resistance of the trial plots, resulting them to be highly effective in reducing the airflow-induced dust emissions (cf. definition for *effective* in Glossary). In addition, the penetrometer test results showed enhanced penetration resistance of the biopolymer-treated trial areas (Figure 4.13), demonstrating the biopolymer treatments' underlying effect. The biopolymers acted by coating the sand particles with a thin film, forming a linked network between soil particles and the biopolymers [81]. During the curing

period, the biopolymer solutions dehydrate, and the inter-particle cohesion of the biopolymer–soil matrix increases, improving the wind erosion resistance of the soil [73, 81, 84].

D15 and D25. The first significant rainfall, 4.3 L/m², occurred between the second and third test days (D8 to D15), followed by a further 8.1 L/m² between the third and fourth test days (D15 to D25). On the actual test days, the soil conditions in the trial areas were dry, indicating that the precipitation had either evaporated or percolated below the soil surface. The dust emissions measured on the biopolymer-treated plots had increased significantly compared to D8 and reached similar or partially even higher levels than the untreated plots (Figures 4.8-4.10). It can be concluded that the significant increase in dust emissions is related to the degradation of the treatments' effectiveness due to rainfall-induced leaching of the water-soluble biopolymers. The visual inspections also revealed cone-shaped erosion traces on the biopolymer-treated plots, with the footprint of these traces increasing from D15 to D25 (Figures 4.11 and 4.12). However, on both days, the extent and depth of the traces were not as pronounced as on the untreated plots (Figures 4.11, 4.12 and C.1-C.4). The penetration resistance measured on the XG-, CS- and FBPC-amended plots also decreased to levels similar to the control, with only the FBPC-amended area still showing elevated resistance.

Although the dust emissions increased significantly on D15 and D25, a closer analysis of the emissions measured for the biopolymer-treated plots indicates that residual effects of the treatments were still present on D15 (for the XG and CS amendments) and probably on D25 (FBPC treatment). On D15, the XG and CS amendments showed lower emissions than the control at all velocities tested, with the XG-treated plot tested at v_3 being the only exception. On D25, the residual effects of the XG and CS treatments appeared to have mostly vanished. By contrast, on D25, the FBPC-amended plots showed notably lower emissions than the control. This is likely due to the moisture retention capacity of FBPC and its higher dosage (4.1 g/m²) compared to XG (0.7 g/m²) and CS (1.3 g/m²). Due to the higher dosage, it had likely not been entirely washed off the surface by rainfall. In addition, Sieger et al. [1] previously found that FBPC displayed increased moisture retention capacity. Thus, it is assumed that the remaining FBPC on the trial area allowed it to retain some moisture from the 6.8 L/m² of rainfall that fell on D23, resulting in slightly reduced dust emissions compared to the control.

D32. Between D29 and D31, significant rainfall of 31.4 L/m² occurred, resulting in wet soil on the fifth test day (D32). This increase in soil moisture content resulted in higher penetration resistance across all trial areas (Figure 4.13). The wet soil conditions also resulted in considerably lower dust emissions measured on D32 (Figures 4.8-4.10), as the moisture agglomerated the sand particles. However, natural cross-winds and occasional wind gusts strongly influenced the fan's airflow direction, distorting the results and preventing a more detailed comparison. The Inden mine weather station recorded a relatively high maximum wind velocity of 10.3 m/s on D32. The effect of the crosswinds is evident in some of the photographs of plots subjected to v_2 (i.e., XG, CS, and C, Figures C.1 and C.2) and v_3 (i.e., CS and C, Figures C.3 and C.4). While the interpretability of the dust emission measurements from D32 is thus limited, the comparison of visual characteristics revealed considerable erosion traces on the biopolymer-treated soil plots, which were still not as pronounced as on the untreated test plot. Hence, the biopolymer treatments probably still had a marginal residual effect on D32.

D38. Between test days five and six (D32 to D38), further rainfall of 11.5 L/m² occurred, resulting in even wetter soil conditions, as reflected by the increased penetration resistance compared to D32 (Figure 4.13). As a result of these wet conditions, only marginal dust emissions were recorded across all trial plots, with mean TSP emissions ranging from 0.05 to 0.12 mg/m³, only slightly above the background level (0.03 mg/m³). The saturated soil conditions also resulted in only marginal wind erosion traces at v_1, which became more pronounced at v_2 and v_3. It is therefore concluded that the very low dust emissions are solely related to the saturated soil,

which prevented the generation of dust emissions.

D45. Before the last test day, 17.3 L/m² rain fell between D39 and D41, followed by 0.4 L/m² three days before D45. On D45, the surface layer of the trial areas appeared to be relatively dry, while the elevated penetration resistance (Figure 4.13) indicated that the underlying soil was still moist. The measured dust emissions were relatively high again, whereby the biopolymer-treated plots still showed slightly lower emissions than the control. Visual inspection of the photographs revealed the typical cone-shaped erosion traces, with the biopolymer-treated plots still showing slightly smaller traces than the untreated plots. It is thus concluded that the biopolymer treatments still had a marginal residual effect on the wind erosion resistance, which was insufficient to notably reduce the dust emissions induced by airflow.

Conclusions. Interpretation of the field trial results revealed that all biopolymer treatments significantly suppressed the dust emissions for the airflows tested for the short term (up to D8). After D8, rainfall leached the water-soluble biopolymers off the soil surface, degrading the effectiveness of the treatments. The conclusion that rainfall leaching appears to be the main factor impairing the treatments' durability is consistent with previous studies (see section 4.4.1 and Table C.6). As the dust emission measurements, visual inspections, and penetrometer results still indicated a significant effect of the biopolymer treatments on D8, the effectiveness of the treatments would likely have lasted longer had no rainfall occurred in the following days. From D15 to D45, the biopolymer-treated plots still mostly showed slightly lower dust emissions and smaller erosion traces than the control, indicating a marginal residual effect that was insufficient for effective dust control.

Effect of Air Velocity on Dust Emissions and Soil Erosion

A comparison of the measured dust emissions revealed the same overall behaviour throughout the field trials for all velocities tested. Thus, regardless of the velocity tested, it can be concluded that the biopolymer treatments significantly reduced the dust emissions up to D8 of the field trials. However, a closer analysis of the dust emissions measured for the different velocities did not reveal a clear trend regarding the effect of wind velocity on the measured dust emissions. This does not align with the expected outcome of dust emissions increasing at higher velocities. For instance, on D2 and D8, emissions increased as the velocity increased from v_1 to v_2, but mostly decreased again at v_3. On D15 and D25, induced air flows at v_2 and v_3 on the treated plots even tended to result in lower emissions than at v_1. In contrast, the untreated plots showed higher emissions as the velocity increased from v_1 to v_2 and either decreased (D15) or stagnated (D25) as the velocity was further increased to v_3.

A possible explanation for the unexpected results described in the previous paragraph was derived from a close analysis of the time series of the individual dust emission test results (section 4.3.2) and the visual observations (section 4.3.3). Figure 4.7 shows that the measured dust emissions tend to decrease more rapidly with increasing velocity after peaking in the first few seconds of each test. This is likely because most soil erosion, and therefore dust generation, occurs in the first few seconds of each test, eroding most of the wind-susceptible sand particles. Therefore, on the one hand, higher velocities resulted in the wind erosion to increase, as evident by the scale of the erosion traces (section 4.3.3), indicating a greater dust generation potential. On the other hand, increasing the velocity also accelerated the wind erosion process and the dissipation of the generated dust, resulting in a rapid decrease in the measured dust emissions. It is assumed that these two counteracting effects, in some cases, resulted in the mean measured dust emissions only changing marginally or even decreasing upon increasing the velocity, despite the increased dust generation. Here, a more enclosed test setup would have prevented the rapid dissipation of the dust generated.

Variability of Dust Emission Data

The results of the field trials partially exhibited a high variability between the replicate measurements (Tables C.2-C.4). Comparison with previous studies showed this to be common for field trials measuring dust emissions (e.g., [121, 228–230]). Furthermore, on D15, D25, and D38, where the effectiveness of the biopolymer treatments was already degraded, the emissions measured on the biopolymer-treated plots partially exceeded those of the untreated plots (Figures 4.8-4.10). Although this contradicts the expectations, results from field trials by Park et al. [140] and Preston et al. [121] show similar trends. Thus, these unexpected trends appear to be common for field trials measuring dust emissions in field settings, and are likely related to the naturally inherent heterogeneity of each soil plot.

4.4.3 Penetration Resistance

Several laboratory studies have used penetrometer tests to investigate the penetration resistance of biopolymer-treated soils [2, 108–112, 114–116], and some have additionally found that the penetration resistance correlates with the wind erosion resistance of the soil [2, 109, 110, 112]. Thus, in the context of laboratory studies, penetrometer tests provide a valuable qualitative indicator for evaluating the potential of a substance to enhance soil wind erosion resistance. However, to date, few field trials have employed penetrometer testing, primarily examining the strength of (biological) soil crusts (e.g., [231–235]). Hence, the value of using the penetrometer in field trials investigating dust suppressants or soil stabilisers has not yet been explored.

Penetrometer analyses in this study revealed that the biopolymer-treated trial areas on D2 and D8 showed notably increased penetration resistance (Figure 4.13), which correlated with low dust emissions measured on the corresponding plots (Figures 4.8-4.10). Vice versa, as dust emissions on the treated plots on D15 and D25 increased due to rainfall-induced degradation of the treatments, the penetration resistance decreased significantly. This indicates that the measured dust emissions tend to be negatively correlated with the penetration resistance, similar to previous laboratory studies that reported a correlation between wind erosion and penetration resistance (i.e., [2, 109, 110, 112]). However, analysis of the subsequent test days showed that this relationship must be examined in the context of the soil conditions. On D32 and D38, the soil surface was wet, resulting in significantly reduced dust emissions and increased penetration resistance, although the effectiveness of the biopolymer treatments had already diminished.

A closer comparison of the penetration resistance showed that it only serves as a relative qualitative indicator of the effectiveness of the treatment, as the differences in penetration resistance between the biopolymer-treated areas are not directly reflected in the dust emissions. For example, on D15 and D25, the FBPC-amended area still showed increased penetration resistance compared to the other areas, while all trial plots displayed similarly high dust emissions. Likewise, on D2 and D8, the XG-treated area had significantly lower penetration resistance than the FBPC- and CS-treated areas, while the respective dust emissions were similarly low on all treated plots. Penetrometer readings are, therefore, rather a supporting indicator for estimating whether a treatment still affects the stability of a treated soil. However, in the context of these field trials, it does not allow inferring differences in the soil erosion resistance between different areas. Thus, it cannot replace the need to conduct airflow-induced dust emission measurements to assess the effectiveness of a treatment.

In this study, the penetrometer analyses provided only limited additional value for interpreting the results of the field trials because they only tested relatively low treatment dosages and a spray-on application, resulting in relatively low resistance and rapid degradation. The method is likely more suitable for field trials testing higher dosages or a mix-in application, where higher resistance can be expected. Regardless, the use of penetrometers is a rapid, low-cost method that provides valuable information on surface soil strength.

4.4.4 Suitability of Test Method

Previous field trials used different experimental setups to measure airflow-induced dust emissions from naturally crusted or amended soils. Some studies employed portable boundary-layer wind tunnels, which facilitate test conditions that reflect natural wind flow and also shield the trial plot from cross-winds (e.g., [119, 225, 236]). While they constitute a sophisticated field trial test setup, they are costly, inflexible, and must be custom-built. The patented portable in situ wind erosion lab (PI-SWERL) constitutes an alternative apparatus that has been used successfully in several previous field trials (e.g., [121, 228–230, 237]).

Unlike the portable wind tunnels or the PI-SWERL, the experimental setup used for these field trials was similar to the setups previously used by Park et al. [140] and Freer et al. [62] and followed a rather simplistic approach, as tests were performed in open, unenclosed conditions (Figure 4.5). However, while this setup allowed visual observation of the wind erosion process, it also resulted in a more rapid dissipation of dust emissions, limiting the ability to investigate the effect of air velocity on the dust emissions (section 4.4.2). In addition, the lack of shielding likely distorted measurements performed during heavy cross-winds, so the setup could probably be improved by equipping it with an enclosure. Nevertheless, the experience gained during the field trials and the analysis of the results showed that this setup constitutes a simple, mobile, and flexible method for measuring the wind erosion resistance and dust emissions of amended soils.

4.4.5 Comparison of Field Trials with Previous Laboratory Studies

These field trials build on previous laboratory studies by Sieger et al., who first assessed the particle agglomeration potential of 14 selected biopolymers by moisture retention, penetrometer, and crust thickness tests [1]. A subsequent wind tunnel study analysed the ability of five previously tested biopolymers to enhance the soil wind erosion resistance [2]. The studies showed that all biopolymers agglomerated the sand particles and enhanced the penetration and wind erosion resistance of the samples, with most of the polysaccharides tested (e.g., XG and CS) proving more effective at lower concentrations than proteins (e.g., FBPC) [1, 2].

The present study completes this series of studies by conducting field trials with three of the previously tested biopolymers. Thus, it is important to examine how the results of the laboratory studies compare with those of the field trials. It must be noted that the comparability between the laboratory studies and the field trials is limited because the field trials were conducted in an uncontrolled environment, and unlike the laboratory studies, tested only one dosage for each of the different biopolymers ($0.7\,g/m^2$ for XG, $1.3\,g/m^2$ for CS, and $4.1\,g/m^2$ for FBPC). This limits the comparison of the effect of biopolymer type and dosage on the effectiveness of a treatment.

Regardless, it can be concluded that the field trial results confirm the laboratory studies' findings. Up to D8, all biopolymer treatments significantly reduced the dust emissions and showed increased penetration resistance compared to the untreated area. On most test days, the polysaccharide-treated plots (XG and CS) displayed comparable or even lower emissions than the FBPC-treated plots, which were applied at a much higher dosage, indicating that the polysaccharides are more effective at lower concentrations than the protein. The XG tested also tended to be more potent than the CS tested, as it displayed similarly low emissions up to D8, despite being applied at a lower dosage. This shows that the findings of the laboratory studies are coherent with the results of the field trials. However, this conclusion does not render the field trials obsolete. Instead, the significant effect of rainfall (and other field conditions) on the degradation of a treatment's effectiveness underlines the need for field trials to determine suitable biopolymer types and application parameters.

4.4.6 Application Potential of Tested Biopolymers as Dust Suppressants on Mine Sites

Airflow-induced dust emission measurements are an established method for evaluating the effectiveness of a dust suppressant treatment (e.g., [62, 121, 140, 167, 228]). The dust emissions tests and visual inspections of these field trials showed that all biopolymer treatments effectively suppressed dust emissions in the short term on undisturbed, barren mine soil. Results on D8 indicated that the treatments would have lasted longer under dry conditions. Further aspects, such as durability, cost-effectiveness, availability, ease of use, and environmental friendliness, must be considered to evaluate the potential of biopolymers as novel dust suppressants. While a comprehensive analysis is beyond the scope of this work, these factors are briefly addressed below.

- *Durability.* Rainfall-induced leaching appears to be the main factor impairing the *durability* (cf. Glossary) of a treatment. Aside from rainfall, biopolymers' environmental degradability also limits the durability of their applications. By contrast, traditional dust suppressants such as chloride salts [48] or synthetic polymer emulsions (e.g., [48, 226]) have shown notably higher durability. This implies that biopolymers require more frequent rejuvenation intervals than conventional dust suppressants to maintain their effectiveness. However, it should be noted that the dosages tested in this study were relatively low compared to previous field trials (Table C.6), and it is assumed that higher dosages would enhance the durability of a treatment.
- *Cost-effectiveness.* A cost-effectiveness analysis must account for costs for the biopolymer, water, equipment, fuel, personnel, and rejuvenation intervals required to maintain the effectiveness of the treatments. This study tested relatively low application dosages (see section 4.2.1). Considering indicative bulk prices for the respective biopolymers (XG = 2.0–3.0 USD/kg [85], CS < 1.0 USD/kg [78], and FBPC = 1.4–2.5 USD/kg [191]), the estimated biopolymer costs for the doses tested in this study are XG = 14–21 USD/ha, CS < 13 USD/ha, and FBPC = 57–103 USD/ha. These indicative biopolymer costs per hectare suggest that equipment, fuel, and labour costs and their durability primarily affect the cost-effectiveness of a biopolymer treatment. The test results and product costs also suggest that the polysaccharides tested (CS and XG) are more cost-effective than the protein FBPC. Further field trials are required to determine the long-term application costs of biopolymers. It is important to note that the optimal dosage, durability, and thus application costs are highly dependent on site-specific characteristics, such as climate, precipitation, and the forces acting on the treated areas.
- *Availability, ease of use, and scalability.* The biopolymers tested in this study are readily available in most regions of the world, as they are derived from widely abundant crops such as corn (CS) and fava beans (FBPC) or are commonly used in the oil and gas and food and beverage industries (XG) [78, 191, 208]. Experience from these field trials has shown that biopolymer solutions can be easily prepared and applied on a large scale using readily available spraying equipment.
- *Environmental friendliness.* The safety data sheets (SDSs) of the corn starch (CS) and fava bean protein concentrate (FBPC) tested classify the substances as food ingredients that do not require classification under European Union Regulation (EC) 1907/2006 (REACH regulation). Similarly, the SDS for technical grade xanthan gum (XG) classifies it as readily biodegradable and not dangerous, so it does not require specific labelling under Regulation (EC) 1272/2008 (CLP Regulation). Based on this information, the biopolymers tested in this study are assumed to be environmentally benign. Conversely, traditional dust suppressants, such as salt brines or petroleum-based products, are not as degradable and may have adverse effects on the surrounding flora and fauna [15, 48]. Steevens et al. [238] highlighted that overexposure to some synthetic polymers during the handling and

application may be carcinogenic to workers. McTigue et al. [15] concluded that there is a lack of comprehensive, independent environmental and toxicity data for many commercial dust suppressants, whose ingredients often remain proprietary. Finally, synthetic polymer ingredients are still predominantly derived from fossil fuels and - unlike the biopolymers tested - are not bio-based.

Thus, it is concluded that the biopolymers tested have the potential to be applied as dust suppressants for short-term dust control on undisturbed and exposed mine soils. While their effective application will likely require more frequent rejuvenation intervals than commercially available products, they are bio-based, can be considered environmentally friendly, have no proprietary formulations, and are readily available.

4.5 Conclusion

This study evaluated the potential of the biopolymers corn starch (CS), fava bean concentrate (FBPC), and xanthan gum (XG) as dust suppressants on large, undisturbed, exposed mine soils by conducting field trials on an overburden dump of the Inden open-cast lignite mine, Germany. The field trials included measurements of dust emissions generated by exposing trial plots to air blowing from an electric fan, visual inspection of tested plots, and penetrometer tests. Based on the results, the following conclusions are drawn.

1. The results of this study demonstrate that the spray-on application of low biopolymer dosages with a tractor-mounted field sprayer allows the effective application of dust suppressants on a large scale.
2. For dust emission measurements, trial plots were exposed to air velocities of up to 17.4 m/s, and the biopolymer treatments tested effectively suppressed the measured dust emissions in the short term up to 8 days (D8) after application. On D2 and D8, mean total suspended particle (TSP) emissions measured on treated plots ranged from 0.05 to 0.27 mg/m^3, while emissions on untreated plots ranged from 4.5 to 39.2 mg/m^3. The findings of the visual inspections and the penetrometer tests support the results of the dust emission measurements. After D8, the effectiveness of the treatments degraded rapidly due to rainfall-induced leaching of the water-soluble biopolymers from the soil surface.
3. The custom-built test setup used to measure the dust emissions from biopolymer-treated soil plots by exposing them to airflow generated by an electric air blower proved to be a simple and flexible method for investigating the wind erosion resistance and dust emissions from soils exposed to variable air speeds.

The results of the field trials provide practical evidence that the spray-on application of biopolymers can effectively mitigate dust emissions on large, exposed, undisturbed mine soils in the short term. The biopolymers tested therefore constitute a promising bio-based and environmentally benign alternative to established traditional dust suppressants.

Chapter 5

General Discussion, Implications, and Recommendations

The general discussion evaluates the achievement of the *Research Objectives* and answers the *Main Research Question* articulated at the beginning of this thesis (section 5.1). Complementary to the main focus of this thesis – investigating biopolymers' functional potential as dust suppressants – section 5.2 discusses further dimensions crucial for a comprehensive evaluation of their dust suppressant potential. After that, section 5.3 derives the main implications of this thesis and is followed by section 5.4, which concludes with recommendations for future work.

5.1 Review of the Presented Research

In order to review the thesis research, the achievement of each study phase's *Research Objective* is first analysed. This is accomplished by critically reflecting on the adequacy of the methods and materials used and by evaluating whether the results allow to conclude that the *Research Objective* has been achieved. After that, the findings of the three research articles are synthesised in section 5.1.4 to answer the *Main Research Question* of this thesis.

5.1.1 Article I: Laboratory Screening Study

Research Objective I:
Evaluate the soil agglomeration potential of a diverse selection of underexplored polysaccharide and protein biopolymers on mine soils by testing specific soil parameters important for their functional potential to act as a dust suppressant.

The purpose of *Research Objective I* was to evaluate the functional ability of selected polysaccharides and proteins to agglomerate mine soil particles and act as dust suppressants by conducting a laboratory screening study (Article I). This section concisely reviews the biopolymer and soil type selection, the employed test and analysis methods, and the results and findings.

Biopolymer selection. A diverse range of proteins and polysaccharides meeting specified selection criteria and whose dust suppressant potential had been studied only insufficiently were selected for this study. This selection was complemented by the intensively studied xanthan gum and lignosulphonate, which served as benchmarks for comparison. The diversity and total number of selected biopolymers are considered sufficient for drawing significant conclusions regarding the effect of the biopolymer class and type on the tested parameters.

Soil type selection. Two different soils were selected with particle size distributions representative of mine soils commonly susceptible to wind erosion. The selected medium-grained and fine-

grained silica sand exhibit a high wind erosion risk due to negligible silt, clay and organic matter fractions and their fine particle sizes and thus meet these criteria. Investigating further soil types was not possible due to the already extensive research scope.

Concentration and application rates. Many of the biopolymers tested in this study have not yet, or only rudimentarily, been tested in contexts of soil stabilisation and dust control. Thus, the concentrations and application rates were selected to lie within the ranges used by previous studies testing other biopolymer types. Only xanthan gum was intentionally tested at significantly lower concentrations, as a broad body of literature has demonstrated its high potency at low dosages.

Test methods and analysis. It was deliberately decided not to conduct standardised soil mechanics test methods, such as unconfined or triaxial compression tests. While such standardised methods allow for better comparability of results, the sample preparation and test conditions do not reflect the real-world application conditions of dust suppressants. Instead, samples were prepared by spray-on application and their moisture retention, penetration resistance and crust thickness, established indicators for evaluating potential dust suppressants, were measured.

Results and findings. All tested biopolymers agglomerated particles and formed crusts of varying thickness, with significantly increased penetration resistances compared to the water-treated control group and partially increased moisture retention on both soil types tested. Thus, all biopolymers tested were *effective* and indicate functional potential to act as dust suppressants, whereby some biopolymers achieved a higher *effectiveness* than others (cf. Glossary). Biopolymer type and concentration significantly affected the penetration resistance, moisture retention, and crust thickness. Some polysaccharides and proteins achieved penetration resistances similar to the benchmark (XG) but required higher concentrations to do so. Most proteins required application at higher concentrations to perform similarly to the polysaccharides.

Achievement of Research Objective I. The methodology and test methods of the laboratory screening study were adequately selected and designed. The laboratory screening study (Article I) successfully evaluated and compared the soil agglomeration potential of selected biopolymers by testing specific soil parameters indicative of their functional potential as dust suppressants. Thus, it is concluded that *Research Objective I* has been achieved.

5.1.2 Article II: Laboratory Wind Tunnel Study

Research Objective II:
Investigate the dust suppressant potential of selected biopolymers in a laboratory wind tunnel study, analysing the wind erosion and penetration resistance of mine soil samples treated with different biopolymer types and application parameters.

Research Objective II aimed to further characterise the dust suppressant potential of selected biopolymers by directly measuring the wind erosion resistance of soil samples treated with different biopolymers, concentrations, and application rates and to investigate whether a correlation exists between wind erosion and penetration resistance. The following paragraphs review the methodology and test methods of the wind tunnel study (Article II) and evaluate whether the study's findings allow to conclude that the *Research Objective II* has been achieved.

Biopolymer selection. Five biopolymers, which showed strong potential in the previous laboratory study, were selected, including xanthan gum as a benchmark. In order to have equal representatives from both biopolymer classes, the remainder of the selection included two proteins and two polysaccharides. Time and logistical constraints limited the study's scope to five biopolymers. The biopolymer selection is therefore considered adequate for this study phase.

Soil selection. The same soil types as tested in the first study phase were selected. A further

soil type was not possible due to time and logistical limitations, as the total number of samples prepared and tested was already extensive (336 in total).

Test methodology and design. The test program was divided into two phases, the first was dedicated to study the effect of the concentration and the second to study the effect of the application rate on wind erosion and penetration resistance. In the second phase, the biopolymers were applied only at their 'plateau concentration' as determined in the first phase. This research design reduced the number of samples required to a feasible level, whilst still ensuring that the effect of the application rate and concentration on the wind erosion and penetration resistance could be analysed. The wind tunnel setup has previously been used by Freer et al. [61, 62], and previous studies by other scholars employed comparable test setups. The penetration resistance was measured by a hand-held pocket penetrometer, which was deemed sufficient for studying the overall relation between wind erosion and penetration resistance. Thus, the test methodology and setup are adequate for achieving *Research Objective II*.

Results and findings. All biopolymer treatments were *effective* and significantly improved the samples' wind erosion resistance on both tested soil types, reaching *dust control effectiveness* $> 99\%$ when applied at their respective *plateau concentration* (cf. Glossary). Most samples experienced minimal soil losses during the repeated wind tunnel cycles. While these findings are consistent with previous wind tunnel studies, greater air velocities or an inclined sample placement would have revealed more distinct differences. The ANOVA revealed that the wind erosion resistance was significantly affected by both biopolymer type and concentration. The application rate did not significantly affect the wind erosion resistance on fine-grained silica sand, likely because the treatments were already applied at their plateau concentrations and the limited maximum velocity of the wind tunnel. The Spearman rank correlation revealed a negative correlation between wind erosion and penetration resistance, implying that pocket penetrometer readings can serve as an indirect indicator for evaluating and comparing the performance of different biopolymer treatments regarding their ability to enhance wind erosion resistance.

Achievement of Research Objective II. Methodology and test methods of the laboratory wind tunnel study were adequately selected and designed. While more challenging wind tunnel test conditions would have revealed more distinct differences among the treatments tested, the study successfully investigated the wind erosion and penetration resistance of biopolymer-treated soil samples prepared with different biopolymers and application parameters. Thus, the research contributed to further characterising the functional potential of biopolymers to act as dust suppressants. It is therefore concluded that *Research Objective II* has been achieved.

5.1.3 Article III: Large-Scale Field Trials

Research Objective III:
Investigate the dust suppressant potential of selected biopolymer treatments in large-scale field trials on barren mine soils, analysing their effectiveness in suppressing airflow-induced dust emissions under real field conditions.

The purpose of *Research Objective III* was to investigate and compare the dust suppressant potential of selected biopolymer treatments under realistic field conditions when applied on a large scale using a field sprayer (Article III). The field trials investigated the ease of large-scale application, analysed biopolymers' *effectiveness* in suppressing dust emissions when exposed to different levels of artificially generated airflow, and examined the durability of the treatments. The following paragraphs critically review the employed methodology and test methods and evaluate whether the results substantiate the accomplishment of *Research Objective III*.

Biopolymer and application parameter selection. The biopolymer selection was based on the two preceding study phases and included the polysaccharides CS and XG, as well as the protein

FBPC, to have substances from both biopolymer classes. The application parameters were chosen based on the wind tunnel study. Hence, the biopolymers and parameters were selected based on the profound findings of the previous research.

Field trial location and soil. The field trial location was well-suited for several reasons. It offered an extensive, barren, undisturbed area with a relatively homogenous soil composition at an operating mine. The mine soil had a similar composition to the sands tested in the previous study phases, and a nearby weather station allowed gathering comprehensive meteorological data to analyse the results. Thus, the field trial location and soil were well-suited for this study.

Biopolymer preparation and application. The biopolymer solutions were prepared and sprayed by a tractor-mounted field sprayer, whose onboard control system ensured uniform driving speeds and pump rates. As no clogging or other malfunctions were observed during the spraying process, it is assumed that the field sprayer achieved a uniform treatment application.

Test methodology. The trial fields were subdivided into sections for each test day to ensure uniform testing across the trial areas. The *effectiveness* of the biopolymer treatments was primarily assessed by subjecting trial plots to different airflows of an electric fan and repeatedly measuring the generated dust concentrations over 45 days. Previous studies followed similar approaches with varyingly complex test and measurement setups. The measurements were complemented by visual observations of the tested trial plots and pocket penetrometer testing to support the interpretation of the dust emission measurements. Hence, the overall testing methodology of the field trials is deemed appropriate.

Results and findings. All biopolymer treatments were highly *effective* in suppressing the dust emissions induced by the tested airflows for the short term (up to day 8). After that, the treatments' *effectiveness* degraded, likely due to rain leaching the biopolymers off the soil surface. The results suggest that the treatments would have lasted longer under dry conditions. Contrary to expectation, analysis of the results revealed no significant effect of the airflow velocity on measured dust emissions. Since the observed scale of the wind erosion traces increased with higher airflow velocities, it is suggested that actual dust emissions were increased. It was concluded that the unenclosed test setup resulted in rapid dissipation of the dust emissions, limiting the ability to measure and compare the actual dust emissions generated by the different airflows. Thus, for future studies, it is recommended to employ more enclosed test setups.

Achievement of Research Objective III. Overall, it is concluded that the methodology and test methods employed for the large-scale field trials were adequately selected and designed, whereby future studies should measure dust emissions in a more enclosed setup. The field trials showed that the biopolymers tested effectively suppressed airflow-induced dust emissions from exposed mine soils over the short term, thus demonstrating their potential as dust suppressants. Therefore, it is concluded that *Research Objective III* has been achieved.

5.1.4 Main Research Question

Main Research Question:
What is the potential of polysaccharide and protein biopolymers as dust suppressants for dust control on barren, undisturbed mine soils?

Regarding the *Main Research Question*, the laboratory screening study (Article I) demonstrated that all polysaccharides and proteins tested agglomerated soil particles on both soils. Thus, all the biopolymers tested display the functional potential to act as dust suppressants. Furthermore, the test results allowed to identify the most potent polysaccharides and proteins and revealed that proteins tend to require application at higher concentrations than polysaccharides to achieve similar performance.

As Article I only evaluated the soil agglomeration potential of biopolymers based on indirect parameters, the laboratory wind tunnel study (Article II) directly investigated the wind erosion resistance of biopolymer-treated soil samples to progress towards answering the *Main Research Question*. The wind tunnel study allowed for direct characterisation of the biopolymers' dust suppressant potential and facilitated the determination of suitable application parameters for future studies. The findings showed that all biopolymer-treated samples had a significantly enhanced wind erosion resistance and revealed a negative correlation between wind erosion and penetration resistance. Article II also found that proteins need to be applied at higher dosages to achieve similar performance as the polysaccharides.

While the studies for Articles I and II were conducted at laboratory scale and conditions, large-scale field trials at realistic field conditions (Article III) were indispensable for answering the *Main Research Question*. The field trials demonstrated that all biopolymer treatments tested significantly reduced the airflow-induced dust emissions in the short term (up to day 8), with rainfall-induced leaching being the main factor impairing their *effectiveness*. Thus, the field trials proved the potential of biopolymers to act as dust suppressants under real field conditions.

Synthesising the results of the three research articles finally allows the *Main Research Question*, "*What is the potential of polysaccharide and protein biopolymers as dust suppressants for dust control on barren, undisturbed mine soils?*" to be answered: The results showed that the wind erosion resistance (Article II) did not only correlate with the penetration resistance (Articles I and II), but also proved to be a good indicator of treatment *effectiveness* at field conditions (Article III). Since all biopolymers tested for Article I significantly increased the penetration resistance of the treated soil samples, it can be deduced that all biopolymers tested in this work can likely be used for the *effective* short-term control of wind-induced dust emissions on barren, undisturbed mine soils. As the field trials tested relatively low treatment doses compared to other dust suppressant studies, the functional potential of biopolymers as dust suppressants is promising, albeit conventional dust suppressant treatments are likely more durable. The dust control potential of the individual biopolymers varies considerably, with some biopolymers requiring notably higher dosages (e.g., FBPC) than others (e.g., XG and CS) to achieve a similar *effectiveness*. Thereby, most proteins require higher dosages than polysaccharides to perform similarly. It is therefore concluded that the *Research Aim* of this thesis, i.e., "*to investigate the potential of polysaccharide and protein biopolymers as dust suppressants on barren, undisturbed mine soils.*", has been achieved.

5.2 Further Criteria Relevant for Evaluating Biopolymers' Dust Suppressant Potential

While the experimental work of this thesis primarily focused on investigating biopolymers' functional potential as dust suppressants on barren mine soils, further criteria relevant to comprehensively evaluating their potential must also be discussed. Therefore, the following sections discuss their economics, availability, ease-of-use, and environmental friendliness and, in part, compare them with salt brines and synthetic polymer products – today's probably most commonly used dust suppressants after water.

5.2.1 Economics

An economic analysis must account for all costs of a single dust suppressant application (i.e., dust suppressant, water, equipment, fuel, and labour) and the rejuvenation intervals required to maintain the effectiveness of a treatment. For comprehensive economic comparisons of different dust control products, McHattie [53] recommended and conducted a life cycle cost analysis. As such an analysis would, however, require extensive further field trials with diverse dust

suppressants and dosages, the following paragraphs discuss more general considerations regarding the economics of biopolymer and conventional dust suppressants.

Rejuvenation Intervals

The rejuvenation intervals required to maintain the effectiveness of a treatment have the most significant impact on the economics of dust control treatments and depend on the durability of a treatment against leaching, biodegradation, mechanical disturbance, and wind forces. For applications on undisturbed land, the field trials and previously published literature concluded that rainfall-induced leaching is the main factor impairing a treatment's effectiveness. Compared to the biopolymer treatments tested in the field trials, literature suggests that conventional dust suppressants, such as synthetic polymer products or salt brines, can achieve significantly higher durability (three to six months) [48, 54, 226]. However, a direct, literature-based comparison of the durability of biopolymers and conventional dust suppressants is limited due to significant differences in the type of application (mix-in/topical), dosage, soil, and area (non-traffic/traffic areas) tested in the respective studies. Though, conventional suppressants are generally considered more durable than the biopolymers tested.

Single Application Costs

For a single application, equipment, fuel and labour costs will likely only differ slightly for different dust suppressants. Instead, the main differences are related to the unit cost of the dust suppressant (USD/kg) and the treatment dosage (g/m²). The unit costs of the biopolymers tested in this work span over a wide range (cf. section 2.2.1). Prices for the polysaccharides, such as the starches (0.4–1.0 USD/kg), CMC (1.4 USD/kg), NLS (0.2–0.5 USD/kg) and XG (2.0–3.0 USD/kg) are significantly lower than for most proteins, such as PP (3.5–4.5 USD/kg), HEA (6.0–8.0 USD/kg), WPC (5.5 USD/kg), and TG (4–6 USD/kg). Only the costs for HG (0.7–1.0 USD/kg), FBPC, and WP (1.4–2.5 USD/kg) are partially comparable with the polysaccharides.

In contrast, the costs of commercial dust suppressants are difficult to compare with each other or with biopolymers due to the limited availability of information on product costs and composition. The few quotable prices that could be found tend to be around 0.4 USD/L for salt brines [239], 1.1 USD/L for petroleum emulsions [239], and 1.4 to 4.0 USD/L for synthetic polymers [240–242]. However, the water contents listed in the safety data sheets (SDS) of salt brine and synthetic polymer products range from 40 to 80 % (cf. [243–245]), and manufacturers often disclose only broad ranges for the volumetric compositions (e.g., [243]).While a detailed comparison of the costs of biopolymers and traditional products is therefore limited, the costs of traditional products (excluding the water content) will usually exceed the costs of most biopolymers.

Dosage (g/m²), which is determined by concentration (%) and application rate (L/m²), is the other key determinant of the cost of a single application. The field trials revealed that relatively low biopolymer dosages already effectively mitigated the airflow-induced dust emissions for the short term. This highlights their potential as a dust suppressant but also implies that further field trials with higher dosages are needed to determine the optimum application parameters for increased durability. In this context, it should be noted that manufacturers and application guidelines also recommend much higher dosages for traditional dust control products (e.g., [48, 54]). In addition, the research results showed that most proteins require application at higher dosages than the polysaccharides to achieve similar performance, suggesting that polysaccharides are likely to be more cost-effective than proteins.

5.2.2 Availability

The biopolymers tested in this thesis can be derived from various plant (cellulose, corn, wheat, pea, fava bean, or potato) and animal (egg, pig, and cow) sources cultivated and bred in most

regions of the world. Biopolymers are, therefore, generally readily available. In addition, grade and specification requirements for dust control purposes are comparatively lower than for other biopolymer applications, such as food additives, pharmaceuticals, cosmetics, or packaging, so that off-grade and off-spec batches with limited marketability can be used for dust control.

Predicting the future supply and demand for biopolymer feedstocks is difficult. Global demand for biopolymer feedstocks will increase over the coming decades as population and wealth continue to grow. Alongside this trend, governments and intergovernmental organisations such as the European Union are striving towards a fossil-free, circular bioeconomy, where fossil fuels for plastics and other products are gradually replaced by biomaterials [246], which will further increase the demand. On the other hand, technological and social innovation will increase biomass productivity and resource efficiency, extend the lifespans of biomaterial products, and change consumer behaviour [246].

5.2.3 Ease-of-use

The ease-of-use of a dust suppressant is crucial to its application potential. This is particularly true in the mining industry, with its sometimes reluctant attitude to new solutions and its large number of small quarries, which often do not have the staff for complex and complicated solutions. The following sections discuss the storage and handling, preparation, and application of biopolymer dust suppressants.

Storage and Handling

In terms of handling and storage, biopolymers have comparatively low requirements. None of the biopolymers tested in this thesis require classification under either European Union Regulation (EC) 1907/2006 (REACH regulation) or EC 1272/2008 (CLP regulation), implying that they are not considered hazardous by these institutions. They are typically available in 25 kg or large bulk bags and have low storage requirements (storage classes 10-13, TRGS 510 [247]). They must be stored in cool, dry, well-ventilated conditions to ensure safe storage and preserve functionality, shelf life and pourability. Large depositions or accumulations of biopolymer dust must be avoided when storing and handling biopolymers to prevent dust explosions. Personal protection with safety goggles, masks and gloves is recommended when handling large quantities in confined spaces. No other special precautions are normally required when storing and handling biopolymers.

Preparation

Except for TG (soluble $> 40\,°C$), all biopolymers tested in this work are readily soluble in cold water without needing pH adjustment. The field trials showed that the biopolymer solutions can be prepared practically in bulk by mixing the required amounts of biopolymer and water with an agitator until complete dissolution. Biopolymers should be added gradually to the water during mixing to avoid clotting, and the concentration should not be too high to ensure good dissolution and sprayable viscosity. For future large-scale applications, the solution preparation can be further improved by preparing concentrated biopolymer solutions in intermediate bulk containers (IBCs) prior to field application, as is also common for many commercial suppressants.

Application

Aside from the field sprayer tested in the field trials, the biopolymer solutions can be applied with various types of equipment, such as hydroseeders [50], wheeled sprinkler carts, fog cannons, or water trucks with spray bars, provided the solution is not too viscous for the pump, pipes, and spraying nozzles of the equipment. Comprehensive guidelines and field handbooks for the

practical application of dust suppressants have been published by Rushing and Tingle [50], Bolander and Yamada [54], and Jones [48]. While their guidelines focus primarily on traditional dust suppressants, they largely apply to biopolymers. High solution viscosities (e.g., TG and XG in Article I) should be avoided to ensure proper spraying and infiltration of the biopolymer solution. This problem can be prevented by increasing the application rate and decreasing the concentration to achieve the same dosage at the cost of increased water consumption. Finally, religious restrictions may prohibit the utilisation of certain animal-based biopolymers in Muslim or Jewish communities or countries. For the biopolymers tested, this applies to porcine haemoglobin protein (HG), porcine plasma protein (PP), and bovine technical gelatine (TG).

5.2.4 Environmental Friendliness

A detailed investigation of the environmental impact of using biopolymers or conventional dust suppressants for dust control requires extensive additional testing and analysis. Hence, the following paragraphs provide a general estimate of the ecotoxicity, biodegradability, circularity, and GHG emissions that would potentially be associated with using biopolymers compared to established traditional dust suppressants.

Ecotoxicity

Ecotoxicity can be defined as the potential of biological, chemical, or physical stressors to affect ecosystems [248]. The effects of dust suppressants on biotic systems must be well characterised and understood, as their use affects not only the soil they are applied to, but they also impact on surrounding ecosystems through leaching spillage, run-off, airborne transport or movement of treated sediments [205]. As pointed out by Kunz et al. [205], bio-based products do not per se have lower effects on biotic systems than conventional dust suppressants, and hence, ecotoxicological testing and environmental risk assessments need to focus on individual formulations rather than broad categories of dust suppressants.

Overall, there is a lack of independent studies investigating the effects of different dust suppressants on biotic systems [14, 15], with a recent study by Kunz et al. [205] testing the aquatic toxicity of different suppressants being one of the few published articles. For most commercial dust suppressants, McTigue et al. [15] criticise a lack of information on their environmental impact and chemical composition - the latter probably for proprietary reasons. Furthermore, the authors criticised insufficient testing by independent third parties [15]. However, it should be noted that this is not the case for all manufacturers, with some also providing certificates and independent test results for their products [249]. The use of salt brines has been linked to elevated chloride concentration in surrounding streams, and impaired tree growth, and may affect aquatic life [14, 15].

In contrast to the proprietary limitations and ambiguities associated with synthetic polymers or the known environmental impacts associated with salt brines, biopolymers offer the advantage of being well-characterised and studied, and the disclosure of information is unlikely to be hampered by trade secrets. Ultimately, however, reliable conclusions about the ecotoxicology of any individual dust suppressant - be it bio-based or synthetic - require testing of its effects on biotic systems. The *OECD Guidelines for the Testing of Chemicals* provide a collection of internationally recognised test methods for analysing the effects of substances on biotic systems [250]. However, this list encompasses 52 different methods tailored for different species, effects, and ecosystems, so appropriate tests must be determined and conducted by experts. In addition, lysimeter studies (cf. [251]) would allow characterisation of the leaching behaviour of dust suppressant treatments exposed to rainfall, as well as analysis of the leachate chemistry.

Biodegradability

Biodegradability is the ability of organic matter to be broken down by biotic (microbial enzymes) and abiotic (e.g., oxidation, photodegradation, and hydrolysis) processes [252, 253]. Thereby, macromolecules are broken down into smaller and smaller molecules until they are mineralised into CO_2, H_2O, and biomass [252, 254]. The rate and extent to which a substance degrades depends on its chemical structure and environmental factors [252]. While all polymers degrade, the time taken to do so can range from a few weeks to centuries, and some polymers may not mineralise completely, leaving residues in the environment. The *OECD Guidelines for the Testing of Chemicals* provide a complex hierarchy of test methods for determining the biodegradability of chemicals and allow classifying them as inherently, readily, ultimately or not biodegradable [255].

The salt contained in brine products is not biodegradable. Rather than degrading, it will gradually leach off the soil, potentially contaminating surface streams or groundwater [14]. By contrast, the biodegradation of biopolymers and synthetic polymers is very complex and highly dependent on their molecular structure. Overall, most biopolymers, such as cellulose and starch, tend to degrade relatively fast [252, 256], while some biopolymers, such as lignin, degrade comparatively slower [256, 257]. Modifying polymers (e.g., pregelatinisation of starches) can also significantly affect their biodegradability [257]. Hahn and Hennecke [256, 257] concluded that synthetic polymers often only degrade slowly but are sometimes even readily biodegradable. Manufacturers of synthetic polymer dust suppressants provide little or no information on the biodegradability of their products (e.g., [258–262]), which has also previously been criticised by Steevens et al. [238] and McTigue et al. [15]. Therefore, although biopolymers, in general, tend to biodegrade more rapidly and mineralise more completely than most synthetic polymers, it is still necessary to perform biodegradability testing on each substance that is to be used as a dust suppressant as a basis for any further considerations.

Circularity

Replacing conventional dust suppressants with biopolymers can contribute to the industry's circularity. Biopolymers can be cultivated and bred indefinitely from renewable feedstocks, such as plants, microbes, or animals [263, 264]. They degrade and mineralise into H_2O, biomass, and CO_2. Photosynthesis can capture the latter into new biomass, resulting in a net-zero addition to the carbon cycle if the biomass degrades at the same rate as it is produced [265], rendering it a circular and renewable resource. Furthermore, biopolymers can be recovered from certain waste streams or by-products of the paper, leather, or food industries. For example, Li et al. [217] obtained carboxymethylcellulose from waste paper streams and used it as a dust suppressant, while Dang and Shan [215] investigated the potential of using collagen degradation products from leather waste for dust control. Similarly, Freer et al. [60] examined the potential of using carbohydrate-containing by-products from the food processing industry as dust suppressants. Such practices would allow to close loops, contributing to a circular economy.

In contrast, established dust suppressant products, such as salt brines or synthetic polymers, are non-renewable and have a linear product life cycle. Once applied to the ground, salt products gradually leach and disperse into the environment. Similarly, synthetic polymers are still predominantly produced from non-renewable fossil fuels via petrochemical pathways that cannot be replenished. It should be noted that fossil-free production pathways for constituents of synthetic polymer products exist, for example, in biorefineries producing bio-ethylene from bio-ethanol [56, 57, 265]. However, as global biorefinery capacity is still small compared to fossil fuel production [265], it is unlikely that synthetic polymer dust suppressant products will soon be produced primarily from bio-based polymers. Therefore, from a circularity and renewability perspective, using biopolymers as dust suppressants is preferable to fossil-based synthetic polymer products.

GHG Emissions

The fact that biopolymers are renewable and circular substances does not necessarily imply that their use as dust suppressants is associated by default with lower GHG emissions than conventional suppressants derived from finite, non-renewable resources. This is because other factors along the life cycle of the substances may offset the benefits of replacing fossil with renewable (bio-)polymers. The net carbon emissions associated with the degradation and mineralisation of biopolymers are zero, if the carbon emissions generated are reabsorbed by organisms growing at the same rate. Thus, the GHG emissions associated with the use of biopolymers as dust suppressants are related to the energy and resources (e.g., nitrogen fertilisers [266]) consumed during their cultivation, transport, manufacturing (e.g., grinding or extrusion) and application. Compared to plant-based biopolymers, animal-based proteins are associated with significantly higher GHG emissions due to the high conversion ratio associated with the conversion of plant to animal proteins [267] and the generally high GHG emission intensity of livestock [268].

As inorganic substances, such as salt products, do not degrade, no GHG emissions are associated with their degradability. In contrast, for synthetic polymers, the emissions associated with their degradation depend on the extent to which they mineralise. The majority of GHG emissions for these two categories are, therefore, related to the emissions associated with their extraction, processing, refining, transport and final use as dust suppressants. In particular, the extraction and refining of synthetic polymers from fossil fuels is known for its GHG emission intensity [269]. Hence, the specific GHG emissions related to the production of synthetic polymers are likely to be higher than for biopolymers.

However, a key determinant in comparing the GHG emissions associated with the different suppressants is the total dust suppressant demand (kg) – given by the dosage (g/m^2) and reapplication intervals – needed to achieve effective dust control for a given surface. As salt and synthetic polymer applications are expected to require less frequent reapplication intervals than biopolymers, the total GHG emissions associated with their use may be even lower than for biopolymers. Thus, further field trials testing the durability of different dust suppressants and more precise data on the GHG footprint associated with the life cycle of the different substances are required for a comprehensive evaluation.

5.2.5 Conclusion

The discussion has shown that the relevant criteria for a comprehensive evaluation of biopolymers and traditional dust suppressants are complex and cannot be conclusively assessed based on existing knowledge. Biopolymers are circular, readily available, easy to use, and likely superior to many traditional suppressants regarding ecotoxicology and biodegradability. However, actual ecotoxicology and biodegradability test data are required for almost any type of dust suppressant – biopolymer or traditional – before any robust conclusions can be drawn. Similarly, also biopolymers' economics and net GHG emissions compared to traditional suppressants cannot yet be assessed conclusively, and further field trials and investigations are required to resolve these uncertainties.

The discussion also revealed that the relationships between economics, biodegradability, and GHG emissions are characterised by interdependencies and trade-offs, and there is unlikely to be one dust suppressant that is superior to all others in all aspects. While from an environmental point of view, dust suppressants should be readily biodegradable, high degradation rates and mobility imply the need for more frequent rejuvenation intervals, resulting in higher dust suppressant consumption and increasing overall costs and GHG emissions. At the same time, each type of dust suppressant is likely to have at least some effect on organisms within the soil and surrounding ecosystems. As a result, the choice of one dust suppressant over another will always be a compromise, and a trade-off between economic and various environmental criteria and

environmental risks must be assessed on a case-by-case basis. Ultimately, the guiding principle for any kind of dust control application should be that the benefits of their use should justify and outweigh any associated adverse environmental impacts.

5.3 Implications

The findings of this thesis have theoretical and practical implications. In the following, section 5.3.1 focuses on the theoretical implications for academia, followed by section 5.3.2 which presents the practical implications for operators.

5.3.1 Theoretical Implications

Previous research has investigated the dust suppressant potential of biopolymers only to a limited extent, and several research gaps remained to be addressed. In particular, previous work has only examined a limited variety of biopolymers, mainly polysaccharides native to tropical or arid climates. Comparative studies with polysaccharides and proteins from diverse sources native to continental climates were needed for a more comprehensive evaluation of their potential. Another major gap was that the effectiveness of biopolymers as dust suppressants had not yet been tested in large-scale field trials under real environmental conditions. This work has addressed these gaps, and the findings lead to the following theoretical implications:

- *Effective at field conditions.* The results of the large-scale field trials provided empirical evidence that biopolymer applications can effectively mitigate wind-induced dust emissions on exposed mine soils in the short term under real field conditions. It was demonstrated that even low doses of biopolymers can effectively control airflow-induced erosion and dust emissions, with rainfall-induced leaching likely to be the main factor impairing their effectiveness. These findings not only underpin the relevance of diverse previous laboratory studies testing biopolymers but also justify and encourage continued and intensified research in the future. Furthermore, the results also suggest that future research should focus on approaches that improve the durability of treatments, possibly by using higher dosages, testing different biopolymers or likely modifying them.
- *Diverse biopolymers have potential.* The results of this work indicate that all the biopolymers tested have potential as dust suppressants. This adds to the existing body of knowledge, as several of the biopolymer types tested, particularly the proteins, have previously not been studied or only rudimentarily. These findings imply that future studies should not focus exclusively on biopolymers, such as guar or xanthan gum, which have already been extensively studied. Instead, they suggest that research should focus on under-researched biopolymers that may be more affordable, regionally available, or potentially derived from waste streams or by-products. Furthermore, due to the comparative nature of this work – testing different biopolymers, application parameters, and soils – the results provide other researchers with a reference for future studies.
- *Simple and cost-effective laboratory screening method.* The methodology of the laboratory screening study proved to be a simple and cost-effective procedure for analysing the particle agglomeration achieved by different biopolymer treatments on selected soils using minimal sample volumes. This methodology may enable other researchers to rapidly evaluate the performance of other biopolymers on different soil types. In addition, the results of the laboratory studies contribute to the understanding of how the concentration and application rate affect moisture retention, crust thickness, penetration and wind erosion resistance resulting from different biopolymers applied to different soil types.
- *Flexible field setup.* Finally, the custom-built test setup and methodology used in the

field trials expanded on the setup previously used by Freer et al. [62]. The setup allows for repeatable measurements while being flexible and simple. Complementing the dust emission measurements with penetrometer readings and visual observations proved to ease the interpretation of the results. These findings suggest that such setups can be recommended for future field trials.

The findings of the thesis also have theoretical implications for related research disciplines exploring environmentally benign approaches to improving the inter-particle cohesion or moisture retention of a soil matrix to achieve a specific engineering purpose. In particular, this applies to related types of dust control applications, geotechnical engineering applications, and research on revegetation and anti-desertification measures:

- *Dust control on unpaved roads.* The findings of this work have implications for dust control practices on unpaved roads, where mechanical disturbance from traffic is the primary source of dust emissions. Previous studies have investigated the effectiveness of synthetic polymers [119, 226, 270], petroleum and bitumen emulsions [119, 226, 270], tree resin [119], salt brines [119, 270–273], and molasses [58, 59]. To date, lignosulphonates [119, 120, 270] and corn starch [272] are the only biopolymers investigated in this application context. The findings of this thesis suggest that the biopolymers tested may also be used as dust suppressants on unpaved roads, which could contribute to more environmentally friendly dust control practices.

- *Active wet spray dust suppression.* The results of this work also have implications for active wet spray dust suppression systems, where dust dispersed in the atmosphere is actively suppressed by spraying systems. Such systems are commonly used at point sources of dust emissions, such as excavator loading points [274], conveyor belt transfers, or shearers in underground longwall mining [275]. Today, plain water is still the most commonly used medium for such systems, but chemical additives are sometimes used to improve wetting and suppression properties. Recently, the potential of biopolymers, such as carboxymethylcellulose, lignosulphonate, and modified sodium alginate, has been explored [274, 275]. The findings of this work suggest that other biopolymers may also show potential as additives to improve the performance of wet spray systems.

- *Geotechnical engineering applications.* Furthermore, the findings suggest that the biopolymers tested in this thesis can also be used for different geotechnical applications, where cementitious binders, such as gypsum, lime, or cement, are still predominantly used. As outlined in the introductory chapter (cf. p. 8ff.), several studies already investigated the potential of different biopolymers for geotechnical applications. However, the results of this work suggest that biopolymers such as plasma protein or technical gelatine, which have not yet been investigated in this context, may also show potential to be used in this application context.

- *Revegetation and anti-desertification.* Finally, the results of this work also have implications for research on revegetation and anti-desertification measures aiming at the recultivation of barren soils. In regions with low rainfall and high wind erosion, revegetation projects are often challenging [129]. Recent studies have found that treatments with beta-glucan [129] or xanthan gum [73, 129, 276] can promote plant germination and plant growth and improve root stability, which has been linked to the effects of increased moisture retention and particle agglomeration caused by the biopolymer treatments. This suggests that the biopolymers tested in this thesis, which were found to improve moisture retention and particle agglomeration, can also be used for revegetation and anti-desertification measures.

5.3.2 Practical Implications

The results of this thesis prove that biopolymers can effectively mitigate wind-induced dust emissions on large, exposed, undisturbed mine soils in the short term under real field conditions. Exemplary application areas at mine sites include tailings dams and beaches, overburden and waste dumps, working benches, inactive areas of open pits, and stockpiles. In particular, the results of this work have the following practical implication for dust control practices in the mining industry:

- *Lowered adoption barriers.* The thesis provides scientific evidence of biopolymers' ability to effectively suppress wind-induced dust emissions and offers operators guidance on how to pilot and implement biopolymers as dust suppressants at their sites. Specifically, the findings inform operators about potentially suitable biopolymer types, application parameters, preparation and application procedures, and simple test methods for evaluating the effectiveness of a treatment. In this way, the research will help to lower the barriers opposing a wider adoption of biopolymers as dust suppressants. Operators deciding to replace the use of plain water or traditional dust suppressants with biopolymers can benefit from the following practical implications:

- *Reduced water consumption.* Mine sites that still use exclusively plain water for dust control on surfaces prone to wind erosion can significantly reduce their freshwater consumption by incorporating biopolymers into their dust control practices. Wind erosion and associated dust emissions are a growing issue in arid, water-scarce regions, and water scarcity is expected to increase in many regions of the world [214, 277]. Water will, therefore, become an increasingly valuable resource. Mine sites that decide to incorporate biopolymers into their dust control practices will be able to reduce their water consumption and likely also the associated costs.

- *Environmentally friendly dust control practices.* Replacing traditional dust suppressants, such as salt brines, synthetic polymers, or petroleum-based products, with biopolymers will contribute to reducing the environmental impacts associated with dust control practices. While many traditional dust suppressants have been shown to affect local and surrounding ecosystems negatively, biopolymers are circular, renewable, regionally available, biodegradable, and considered to be more environmentally friendly than traditional products.

- *Social license to operate.* In recent years, earning the social license to operate has emerged as one of the key challenges facing the mining industry [278–280]. The general public and local communities often have low levels of trust [281] and perception [282] of the industry. Dust emissions are often one of the main nuisances experienced by local communities living near mine sites. In order to earn the social license to operate, mining companies are therefore challenged to operate more responsibly and can contribute to this by reducing the dust emissions from their mine sites in a more environmentally friendly manner. Replacing traditional dust suppressants with bio-based substances, such as biopolymers, contributes to more environmentally friendly dust control practices, increases trust and improves the perception among local residents. In addition, it may be possible to procure certain biopolymers locally from regional producers, which can further contribute to the social license to operate.

5.4 Recommendations

Based on the findings and experiences gained during the thesis research, the in-depth literature review and the conversations with mine operators that accompanied the research, several recommendations can be made for future work. Therefore, a distinction is made between recommendations for academia (section 5.4.1), operators (section 5.4.2), and authorities, policymakers, and industry associations (section 5.4.3).

5.4.1 Academia

For academia, the following recommendations for future work can be made:

- *Optimum application dosages.* The biopolymer dosages tested in the field trials provided only short-term effective dust control, and further field trials are needed to determine optimum application dosages for selected biopolymers. The results of such field trials would pave the way for comparative studies testing biopolymers and established dust suppressants under comparable conditions.
- *Comparative field trials with different dust suppressants.* There is a need for long-term field trials, preferably with multiple rejuvenation intervals, investigating various selected types of dust suppressants (including biopolymers) in a comparative setting. This would facilitate to comprehensively evaluate and compare different dust suppressants regarding their effectiveness, durability, economics, water and product consumption, and associated GHG footprint.
- *Biodegradability and ecotoxicity testing.* Dust suppressants' environmental fate and ecotoxicity remain insufficiently studied [15], with only a few studies addressing this issue [205, 283]. Future studies should investigate these factors by conducting tests according to internationally accepted protocols, such as those provided by the *OECD Guidelines for the Testing of Chemicals* under *Section 2* (effects on biotic systems) and *Section 3* (environmental fate and behaviour)[250, 255].
- *Biopolymer modification for enhanced durability.* The durability and susceptibility to water leaching are main limitations of biopolymers in comparison to traditional dust suppressants. Modification methods such as etherification, cross-linking, or graft copolymerisation hold potential to improve the industrial utility of biopolymers [284]. For instance, the process of graft copolymerisation introduces functional groups onto the backbone of biopolymers and can alter their solubility, rheological properties, degradability, or other properties [285]. While the need for biodegradable dust suppressants remains undisputed, such modification methods hold potential to enhance the durability of biopolymers.
- *Mix-in versus spray-on.* The differences between mix-in and spray-on application regimes regarding cost, effectiveness, and durability for different dust suppressants remain insufficiently studied. Future field trials should investigate these aspects. This would contribute towards identifying recommendable application regimes and dosages for dust control on barren undisturbed soils, as well as more challenging application areas, such as unpaved roads.

5.4.2 Operators

For operators at mine sites and other industries experiencing wind erosion and dust emissions from exposed soils, the following rather hands-on focussed recommendations can be made:

- *Gain first-hand experience.* Operators are recommended to gain first-hand experience by conducting small or large-scale field trials. The field trials in this thesis have demonstrated

that biopolymer applications can be easily tested already in low quantities without special equipment or protocols. At its simplest, solutions can be prepared and sprayed onto a small trial plot of soil with a watering can.

- *Search for local manufacturers.* For the selection of biopolymers, mine operators are recommended to search for potential producers in the region surrounding their sites. For instance, this could be paper mills, starch manufacturers, food processing factories, abattoirs, or leather-producing companies.
- *Share experiences.* Employees at many mine sites are often unaware that other dust suppressants than plain water or salt brines exist. Operators gaining first-hand experience with environmentally benign dust suppressants, such as biopolymers, should share their experiences at conferences or other industry gatherings.
- *Determine costs and water consumption of current dust control measures.* Operators using only water as a dust suppressant are advised to determine their current dust control costs. This will allow them to estimate how much money and water they could save through reduced rejuvenation intervals resulting from integrating biopolymers into their dust control practices.

5.4.3 Authorities, Policymakers, and Industry Associations

The following recommendations are made to mining authorities, policymakers and industry associations:

- *Educate and support the industry.* Personal conversations with various mine operators have shown that many mines use only water for dust control, often unaware that other dust suppressants exist and could even save costs. It is believed that a lack of expertise or human resources often prevents the piloting and implementation of more environmentally friendly practices. Here, authorities and industry associations could provide more support by organising information events to educate operators. In this context, especially dust control practices are low-hanging fruits due to their low implementation barriers.
- *Support research.* Today, government funding programmes on environmental conservation expect proposals that focus on cutting-edge technologies, such as remote sensing, machine learning, or artificial intelligence. Comparatively low-tech approaches to reducing environmental impacts, such as biopolymer-based dust control, are often not eligible for funding. Therefore, policymakers should also provide funding programmes that support comparably low-tech solutions, which could have a large impact.
- *Award and promote success stories.* While many industry associations already award prices to mining operations that employ best practices in sustainability, biodiversity, energy efficiency, etc. future awarding ceremonies could especially focus on environmentally friendly dust control practices. Such incentives would help to raise awareness within the industry.

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Appendix A

Article I: Laboratory Screening Study

Table A.1: Compilation of previous studies investigating biopolymer applications in the disciplines of soil stabilisation and dust control.

Biopolymer	Source	Solubility	Type of Application	References
Polysaccharides				
Arabic gum (Acacia gum)	Exudate from acacia trees	Cold-water soluble	Spray-on (dust control)	[110]
			Mix-in (soil stabilisation)	[110, 151]
Agar gum	Red algae (Gelidium and Gracilaria)	Hot-water soluble (>86 °C)	Mix-in (soil stabilisation)	[129, 154, 156]
β-glucan	Extracted from cells of yeast, fungi, certain bacteria and cereals	Cold-water soluble	Mix-in (soil stabilisation)	[124, 129, 134] [103, 286–288]
Carrageenan	Red algae (Chondracanthus)	Cold-water soluble	Spray-on (dust control)	[99, 159]
			Mix-in (soil stabilisation)	[99, 118]
Chitosan	Chitin shells of crustaceans	Soluble in acetic solutions)	Mix-in (soil stabilisation)	[74, 90, 102, 130, 162, 289]
			Spray-on (dust control)	[143, 159, 290]
Carboxymethyl cellulose	Cellulose derivative	Cold-water soluble	Mix-in (soil stabilisation)	[86, 107, 136, 291]
Dextran	Microbial		Spray-on (dust control)	[111, 112]
			Mix-in (soil stabilisation)	[292]
			Spray-on (dust control)	[293]
Gellan gum	Bacteria	Poor solubility at low temperature (fully dissolvable >80 °C	Mix-in (soil stabilisation)	[75, 100, 125, 136, 160, 294, 295]
Guar gum	Guar beans	Cold-water soluble	Mix-in (soil stabilisation)	[103, 108, 109, 124, 136] [89, 93, 132, 138, 148]
			Spray-on (dust control)	[111, 114, 144]
Lignosulphonate	By-product of wood pulp production	Cold-water soluble	Spray-on (dust control)	[109, 119, 180, 274]
Locust bean gum	Carob tree seeds		Mix-in (soil stabilisation)	[88]
Pectin	Citrus fruit lamella and cell walls)	Cold-water soluble	Spray-on (dust control)	[110]
Persian gum	Exudate from almond tree trunk and branches	Cold-water soluble (30% soluble, 70% insoluble)	Mix-in (soil stabilisation)	[152]
Sodium alginate	Brown algae	Cold-water soluble	Spray-on (dust control)	[64, 110, 144, 275]
			Mix-in (soil stabilisation)	[74, 110, 127, 296–299]
Starch				
Corn	Corn	Cold-water soluble	Spray-on (dust control)	[168]
			Mix-in (soil stabilisation)	[118, 156]
Potato	Potato	Cold-water soluble	Spray-on (dust control)	[169]
Xanthan gum	Bacteria	Cold-water soluble	Spray-on (dust control)	[112, 141]
			Mix-in (soil stabilisation)	[124, 133, 138, 300] [101, 105, 146, 301]
Proteins				
Casein	Milk	Soluble in alkaline solutions	Mix-in (soil stabilisation)	[91, 126, 128, 164, 302, 303]
Bovine blood plasma	Bovine blood			[165]
Gelatin	Collagen from animal bones and tissues	Warm-water soluble (>40 °C)	Spray-on (dust control)	[169, 172]
Soybean	Soybean	Cold-water soluble	Spray-on (dust control)	[171, 304]

Table A.2: Moisture retention of medium-grained sand and fine-grained silica sand samples treated at biopolymer concentrations of 1 and 2 wt% (XG = 0.25 and 0.50 wt%. Tests were performed in triplicates ($n = 3$), with M = mean and SD = standard deviation. On medium-grained sand the water-treated control group achieved a mean moisture retention of 6.9 wt% ($SD = 1.2$) and on fine-grained silica sand 2.5 wt% ($SD = 0.7$).

	Moisture Retention (wt%)							
	Medium-Grained Sand				**Fine-Grained Silica Sand**			
	1 wt%		**2 wt%**		**1 wt%**		**2 wt%**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Polysaccharides								
Carboxymethyl cellulose	6.3	3.1	5.8	0.5	4.0	0.9	4.1	0.1
Corn starch	16.1	3.6	13.6	1.0	1.5	0.5	2.7	0.1
Sodium lignosulphonate	9.2	2.7	11.2	1.6	1.7	0.3	3.7	1.2
Pea starch	7.8	0.9	4.6	0.2	1.0	0.3	2.1	0.8
Potato starch	5.3	0.5	5.3	0.7	1.5	0.1	2.5	0.1
Wheat starch	6.2	0.5	12.3	1.7	5.1	0.9	7.2	1.5
Xanthan gum	3.4	0.2	4.0	0.9	6.2	0.9	2.5	0.3
Average	7.8	3.8	8.1	3.8	3.0	1.9	3.6	1.6
Proteins								
Fava bean protein concentrate	12.7	3.7	14.5	1.2	14.0	1.0	17.2	0.8
Hen egg albumen	12.3	2.0	12.4	1.7	1.6	0.2	2.3	0.0
Haemoglobin protein	7.0	1.9	4.9	3.2	13.1	2.4	18.2	2.0
Plasma protein	3.2	0.4	2.4	0.1	1.4	0.2	2.1	0.0
Technical gelatin	17.9	0.9	19.5	3.0	14.0	1.2	12.7	0.6
Wheat protein	15.6	1.0	19.0	2.7	2.0	0.4	2.1	0.2
Whey protein concentrate	5.2	2.0	5.3	2.1	1.2	0.1	2.8	0.1
Average	10.5	5.1	11.1	6.5	6.7	6.0	8.2	7.0

Table A.3: Penetration resistance of medium-grained and fine-grained silica sand samples treated at biopolymer concentrations of 1 and 2 wt% (XG = 0.25 and 0.50 wt%). Tests were performed in triplicates ($n = 3$), with M = mean and SD = standard deviation. The water-treated control group achieved a penetration resistance of 1.5 N ($SD = 0.1$) on medium-grained sand and 1.7 N ($SD = 0.2$) on fine-grained silica sand.

	Penetration Resistance (N)							
	Medium-Grained Sand				**Fine-Grained Silica Sand**			
	1 wt%		**2 wt%**		**1 wt%**		**2 wt%**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Polysaccharides								
Carboxymethyl cellulose	11.5	2.0	21.1	3.6	14.9	3.2	16.4	2.9
Corn starch	14.2	2.0	27.4	4.4	18.0	4.8	25.4	8.6
Sodium lignosulphonate	1.7	0.2	4.3	1.3	14.2	3.1	21.1	3.1
Pea starch	8.0	1.2	20.1	4.3	10.8	2.2	14.4	1.1
Potato starch	4.4	0.6	16.8	1.3	10.1	1.7	19.0	1.6
Wheat starch	13.3	0.9	14.4	2.1	10.0	1.3	8.8	0.4
Xanthan gum	12.4	5.5	26.5	3.9	20.7	5.3	16.0	2.8
Average	9.4	4.5	18.7	7.3	14.1	3.8	17.3	4.9
Proteins								
Fava bean protein concentrate	8.8	2.9	15.9	1.7	15.0	4.1	30.3	3.9
Hen egg albumen	2.5	0.7	5.6	3.0	10.8	2.4	13.9	0.6
Haemoglobin protein	2.1	0.5	10.2	1.7	6.7	1.9	11.2	2.7
Plasma protein	3.5	1.6	15.4	2.8	15.8	2.6	21	4.8
Technical gelatin	8.0	0.2	34.0	6.0	20.0	4.5	37.9	2.1
Wheat protein	3.5	1.2	13.5	3.8	9.1	0.9	18.5	2.9
Whey protein concentrate	2.4	0.5	2.5	0.7	10.0	1.0	15.6	3.2
Average	4.4	2.6	13.9	9.5	12.5	4.3	21.2	8.9

Table A.4: Mean modulus of elasticity (M_e) of crusts formed on medium-grained and fine-grained silica sand samples treated at biopolymer concentrations of 1 and 2 wt% (XG = 0.25 and 0.50 wt%). Tests were performed in triplicates ($n = 3$), with M = mean and SD = standard deviation. The water-treated control group formed no crust, so no M_e could be derived.

	Modulus of Elasticity (kN× m^{-1})							
	Medium-Grained Sand				**Fine-Grained Silica Sand**			
	1 wt%		**2 wt%**		**1 wt%**		**2 wt%**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Polysaccharides								
Carboxymethyl cellulose	17.2	4.0	21.7	5.7	20.7	4.3	20.7	6.3
Corn starch	27.7	14.1	27.2	5.9	69.1	50.5	38.7	26.2
Sodium lignosulphonate	0.6	0.1	3.7	2.1	22.2	9.1	28.7	6.4
Pea starch	6.8	1.4	20.1	3.2	24.2	8.3	43.4	18.8
Potato starch	4.8	0.3	20.2	6.2	25.7	5.9	65.0	13.9
Wheat starch	15.9	1.5	13.2	3.0	8.6	2.4	7.4	0.7
Xanthan gum	23.9	9.3	36.0	11.4	41.2	12.1	20.7	3.5
Average	13.8	9.4	20.3	9.4	30.2	18.2	32.1	17.5
Proteins								
Fava bean protein concentrate	13.0	8.6	21.1	5.0	36.3	7.8	87.2	44.8
Hen egg albumen	1.3	0.3	7.4	3.3	19.7	9.3	26.3	3.7
Haemoglobin protein	1.2	0.2	13.1	5.6	14.1	7.1	27.3	12.8
Plasma protein	4.3	3.1	18.3	9.3	22.7	6.1	30.9	3.0
Technical gelatin	9.4	1.4	31.2	5.3	32.8	9.3	33.7	6.2
Wheat protein	3.7	2.8	13.8	3.8	14.1	3.7	47.0	16.6
Whey protein concentrate	1.8	1.6	1.5	0.5	19.9	2.6	22.4	6.2
Average	5.0	4.2	15.2	8.9	22.8	8.0	39.3	20.9

Note. *Medium-grained sand.* For 1 wt% treatments, the Me of polysaccharides-induced crusts was on average 2.8 times greater than the Me of protein-induced crusts. Amendments with CMC, CS, and XG resulted in the highest Me among the tested polysaccharides and FBPC and TG among the tested proteins, respectively. Doubling the concentration resulted in the Me of most biopolymer-induced crusts increasing, whereby protein-induced crusts exhibited a disproportionate increase relative to the polysaccharide-induced crusts. *Fine-grained silica sand.* On samples treated at 1 wt% biopolymer concentration, polysaccharide-induced crusts on average exhibited a larger Me than protein-induced crusts, with CS, XG, FBPC, and TG achieving the highest Me within their respective groups. Treatment at 2 wt% increased the Me of most biopolymer treatments tested, with protein-induced crusts increasing disproportionately in thickness relative to the polysaccharide-induced crusts.

Table A.5: Mean crust thickness of medium-grained sand and fine-grained silica sand samples treated at biopolymer concentrations of 1 and 2 wt% (XG = 0.25 and 0.50 wt%). Tests were performed in triplicates ($n = 3$), with M = mean and SD = standard deviation. Water-treated control groups formed no crusts.

	Crust Thickness (mm)							
	Medium-Grained Sand				**Fine-Grained Silica Sand**			
	1 wt%		**2 wt%**		**1 wt%**		**2 wt%**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Polysaccharides								
Carboxymethyl cellulose	6.3	1.6	7.1	0.4	9.6	0.5	9.3	0.2
Corn starch	7.5	0.3	5.9	0.8	7.7	0.5	7.3	1.0
Sodium lignosulphonate	2.4	1.0	4.6	0.9	13.1	0.3	18.1	2.7
Pea starch	6.3	0.2	6.9	0.4	8.3	0.6	7.0	0.2
Potato starch	3.4	0.5	7.3	0.2	11.7	0.4	13.7	0.2
Wheat starch	6.3	0.4	4.7	1.6	3.2	1.3	2.4	0.5
Xanthan gum	6.6	0.1	5.9	0.1	7.3	0.4	5.8	0.3
Average	5.5	1.8	6.1	1.0	8.7	3.0	9.1	4.9
Proteins								
Fava bean protein concentrate	7.6	0.4	8.8	0.1	11.6	0.4	11	2.1
Hen egg albumen	0.4	0.4	2.8	0.9	11.0	0.9	13.1	0.3
Haemoglobin protein	0.3	0.4	6.8	0.5	9.2	1.0	8.9	0.6
Plasma protein	5.2	0.8	7.0	0.2	9.4	0.6	11.8	0.3
Technical gelatin	2.3	0.7	5.8	0.4	10.1	0.6	9.4	0.3
Wheat protein	5.5	0.5	8.1	1.2	7.6	2.4	8.3	0.2
Whey protein concentrate	4.0	0.5	4.7	1.7	8.2	0.2	9.5	0.6
Average	3.6	2.6	6.3	1.9	9.6	1.3	10.3	1.6

Table A.6: Qualitative classification of biopolymers according to their crust's visual appearance (cf. Figures 2.10 and 2.11)

Classification	Biopolymers	Description
Medium-Grained Sand		
Solid crusts	Polysaccharides: CS, CMC, WS, XG Proteins: FBPC, TG	1 and 2 wt% (XG = 0.25 and 0.50 wt%) concentrations. Crusts were recoverable in a single piece or up to four fully recoverable pieces.
Mediocre crusts	Polysaccharides: PES, POS Proteins: PP, WP, WPC	1 wt% concentration. Crusts broke into multiple large pieces, whereby some pieces were only partially recoverable and crumbled into countless pieces. 2 wt% concentration. Crusts were almost fully recoverable in several pieces.
Weak crusts	Polysaccharides: NLS Proteins: HEA, HG	1 wt% concentration. Crusts were very weak and brittle, crumbling into countless unrecoverable pieces. 2 wt% concentration. Crusts had increased stability but were still extremely fragile.
Fine-grained Silica Sand		
Solid crusts	Polysaccharides: CS, CMC, PES, XG	1 and 2 wt% (XG = 0.25 and 0.50 wt%) concentrations. Crusts were recoverable in a single piece or up to four fully recoverable pieces.
Mediocre crusts	Polysaccharides: NLS, POS Proteins: FBPC, HEA, HG, PP, TG, WP, WPC	1 and 2 wt% concentrations. Crusts were thick and almost fully recoverable in a few pieces at both concentrations. The uppermost part of the TG crust peeled off from the lower part while recovering the crust.
Ductile crusts	Polysaccharides: WP	1 and 2 wt% concentrations. Crusts were very thin and ductile and even curled up during the curing period.

Table A.7: Compilation of results from previous studies performing penetrometer testing on biopolymer-treated soil samples.

Biopolymer	Soil	D_{50} (mm)	C_u	Penetrometer		AR	Maximum Penetration Resistance (N) at Different Tested Concentrations (wt%)											Ref
				Shape	d (mm)	(L/m²)	0	0.3	0.5	0.6	0.7	0.8	1.0	1.5	1.6	2.0	3.0	5.0	
Acacia gum	Poorly graded sand (SP)	0.15 [a]	2.1 [a]	flat	6	1.3	1.1 [a]		10.0 [a]				15.0 [a]			21.0 [a]	30.0 [a]	50.0 [a]	[110]
		0.15 [a]	2.1 [a]	flat	6	3.5	6.4 [a]		18.0 [a]				20.0 [a]			50.0 [a]	70.0 [a]	145.0 [a]	[110]
Sodium alginate		0.15 [a]	2.1 [a]	flat	6	1.3	1.1 [a]		9.0 [a]				17.5 [a]			18.0 [a]	15.0 [a]	N/A	[110]
		0.15 [a]	2.1 [a]	flat	6	3.5	6.4 [a]		7.5 [a]				21.0 [a]			25.0 [a]	N/A	N/A	[110]
Pectin		0.15 [a]	2.1 [a]	flat	6	1.3	1.1 [a]		15.0 [a]				20.0 [a]			28.0 [a]	22.0 [a]	15.0 [a]	[110]
		0.15 [a]	2.1 [a]	flat	6	3.5	6.4 [a]		20.0 [a]				39.0 [a]			33.0 [a]	30.0 [a]	N/A	[110]
Carboxymethyl cellulose	Poorly graded sand with silt (SP-SM)	0.16 [a]	2.2 [a]	flat	6	1	0.0 [b]	1.0 [b]	2.2 [b]		2.3 [b]								[111]
		0.16 [a]	2.2 a	flat	6	2	0.0 [b]	2.8 [b]	3.6 [b]		5.7 [b]								[111]
Guar gum		0.16 [a]	2.2 [a]	flat	6	1	0.0 [b]	0.7 [b]	1.4 [b]		2.4 [b]								[111]
		0.16 [a]	2.2 a	flat	6	2	0.0 [b]	2.3 [b]	2.8 [b]		3.5 [b]								[111]
Guar gum	Mine tailings	0.15 [a]	33.9 [a]	flat	6	1.9	212.8			263			358.8		428				[111]
Xanthan gum		0.15 [a]	33.9 [a]	flat	6	1.9	212.8			250.8			304.5		340.6				[116]
Xanthan gum	Mine tailings	0.13 [a]	56.3 [a]	flat	6	1.9	213.8	278.4	312.5			331.8							[115]
Xanthan gum	Hooralazim lagoon sand	0.22 [a]	7.5 [a]	flat	6	1.9	5.0 [a]		22.0 [a]				28.0 [a]	32.0 [a]					[112]
	Urmia lake sand	0.13 [a]	2.1 [a]	flat	6	1.9	5.0 [a]		6.0 [a]				6.0 [a]	11.0 [a]					[112]
	Mine tailings	0.28 [a]	9.4 [a]	flat	6	1.9	12.0 [a]		14.0 [a]				27.0 [a]	30.0 [a]					[112]
Carboxymethyl cellulose	Hooralazim lagoon sand	0.22 [a]	7.5 [a]	flat	6	1.9	5.0 [a]		15.0 [a]				38.0 [a]	58.0 [a]					[112]
	Urmia lake sand	0.13 [a]	2.1 [a]	flat	6	1.9	5.0 [a]		14.0 [a]				16.0 [a]	28.0 [a]					[112]
	Mine tailings	0.28 [a]	9.4 [a]	flat	6	1.9	12.0 [a]		18.0 [a]				27.0 [a]	30.0 [a]					[112]
Guar gum	Hooralazim lagoon sand	0.22 [a]	7.5 [a]	flat	6	1.9	5.0 [a]		8.0 [a]				28.0 [a]	39.0 [a]					[112]
	Urmia lake sand	0.13 [a]	2.1 [a]	flat	6	1.9	5.0 [a]		10.0 [a]				14.0 [a]	20.0 [a]					[112]
	Mine tailings	0.28 [a]	9.4 [a]	flat	6	1.9	12.0 [a]		16.0 [a]				25.0 [a]	31					[112]
Sodium alginate + $CaCl_2$	Poorly graded sand (SP)	0.24 [a]	1.7	flat	6	2.2	N/A		2.8 [c]				5.4 [c]			5.4 [c]			[64]

Note. AR = application rate, N/A = not available, SP = poorly graded sand, SP-SM = poorly graded sand with silt, [a] = values extracted from diagram in source, [b] = original values given in kPa and converted into N by multiplying with pin area, [c] = results from pocket penetrometer tests. Original values given in kg/cm² and converted into N using penetrometer pin area and g = 9.81 m/s².

Table A.8: Compilation of results from previous studies performing penetrometer testing on biopolymer-treated red sand (bauxite residue) samples.

Biopolymer	Soil	D_{50} (mm)	C_u	Penetrometer		AR	Maximum penetration resistance (N) at different tested concentrations (wt%)												Ref
				shape	d (mm)	(L/m²)	0	0.4	0.8	1	1.2	1.6	2	3	4	5	6	8	10	
Polyacrylamide	Red loam sand (SP)	N/A	<5	cone	2	2	3.0 [a]	5.5 [a]	7.5 [a]		9.5 [a]	15.0 [a]								[114]
Guar gum		N/A	< 5	cone	2	2	3.0 [a]	5.5 [a]	7.0 [a]		7.5 [a]	8.5 [a]								[114]
Xanthan gum		N/A	< 5	cone	2	2	3.0 [a]	5.5 [a]	6.5 [a]		7.0 [a]	7.5 [a]								[114]
Polyacrylamide	Red loam sand (SP)	N/A	< 5	cone	2	2	N/A	6.0 [a]	8.0 [a]		9.8 [a]									[117]
Guar gum		N/A	< 5	cone	2	2	N/A	5.5 [a]	7.0 [a]		8.0 [a]									[117]
Xanthan gum		N/A	< 5	cone	2	2	N/A	5.3 [a]	6.5 [a]		7.0 [a]									[117]
Sodium lignosulphonate	Red loam sand (SP)	N/A	< 5	cone	2	2	3.0 [a]			4.8 [a]			5.0 [a]	5.3 [a]	6.5 [a]	7.5 [a]	7.8 [a]	8.0 [a]	9.5 [a]	[113]
Calcium lignosulphonate		N/A	< 5	cone	2	2	3.0 [a]			3.5 [a]			4.0 [a]	4.5 [a]	5.0 [a]	5.3 [a]	5.8 [a]	6.3 [a]	7.3 [a]	[113]
Polyacrylamide	Red sand (d < 0.15)	N/A	N/A	cone	2	2	3.2	6.2	7.8		9.6	12.3	15.3							[108]
	Red sand (0.15 < d < 0.3)	N/A	N/A	cone	2	2	3.2	7.4	9.6		11.4	14.2	16.5							[108]
	Red sand (0.3 < d < 0.45)	N/A	N/A	cone	2	2	3.3	8.1	11.1		13.2	16	18							[108]
Guar gum	Red sand (d < 0.15)	N/A	N/A	cone	2	2	3.2	5.7	7		8.3	9.3	10.2							[108]
	Red sand (0.15 < d < 0.3)	N/A	N/A	cone	2	2	3.2	6.7	9		10.2	11.7	14.2							[108]
	Red sand (0.3 < d < 0.45)	N/A	N/A	cone	2	2	3.3	7.1	9.9		11	12.8	14.4							[108]
Xanthan gum	Red sand (d < 0.15)	N/A	N/A	cone	2	2	3.2	5.4	6.4		7.2	7.7	8.1							[108]
	Red sand (0.15 < d < 0.3)	N/A	N/A	cone	2	2	3.2	5.7	6.9		8.6	10.8	13.5							[108]
	Red sand (0.3 < d < 0.45)	N/A	N/A	cone	2	2	3.3	6.5	8		10	12.3	13.4							[108]
Sodium lignosulphonate	Red sand (d < 0.15)	N/A	N/A	cone	2	2	3.0 [a]						5.0 [a]		7.0 [a]		7.5 [a]	8.0 [a]	9.0 [a]	[109]
	Red sand (0.15 < d < 0.3)	N/A	N/A	cone	2	2	3.0 [a]						6.5 [a]		8.0 [a]		9.0 [a]	10.5 [a]	13.0 [a]	[109]
	Red sand (0.3 < d < 0.45)	N/A	N/A	cone	2	2	3.0 [a]						6.0 [a]		8.5 [a]		10.0 [a]	12.5 [a]	14.0 [a]	[109]
Calcium lignosulphonate	Red sand (d < 0.15)	N/A	N/A	cone	2	2	3.0 [a]						3.5 [a]		4.0 [a]		5.5 [a]	6.5 [a]	7.5 [a]	[109]
	Red sand (0.15 < d < 0.3)	N/A	N/A	cone	2	2	3.0 [a]						4.0 [a]		5.5 [a]		7.0 [a]	8.5 [a]	11.5 [a]	[109]
	Red sand (0.3 < d < 0.45)	N/A	N/A	cone	2	2	3.0 [a]						5.0 [a]		6.0 [a]		8.0 [a]	10.0 [a]	12.5 [a]	[109]

Note. AR = application rate, N/A = not available, SP = poorly graded sand, SP-SM = poorly graded sand with silt, [a] = values extracted from diagram in source, [b] = original values given in kPa and converted into N by multiplying with pin area, [c] = results from pocket penetrometer tests. Original values given in kg/cm² and converted into N using penetrometer pin area and g = 9.81 m/s².

Table A.9: Compilation of results from previous studies analysing the crust thickness of biopolymer-treated soils.

Biopolymer	Soil Type	AR	Crust Thickness (mm) at Different Tested Concentrations (%)																	Ref
		(L/m²)	0	0.3	0.4	0.5	0.7	0.8	1	1.2	1.6	2	3	4	5	6	7	8	9	10	
Acacia gum	Poorly graded sand (SP)	1.3				7.4–11.9			5.1–11.4			5.2–11.5	3.8–10.9		2.8–10.9						[110]
Sodium alginate		1.3				8.5–15.3			7.6–15.2			2.2–10.3	3.0–6.7								[110]
Pectin		1.3				3.8–8.4			3.6–7.3			4.6–6.1	2.4–3.0		0.9–1.2						[110]
Acacia gum		3.5				15.1–29.8			12.6–29.3			11.5–22.1	11.5–22.0		9.7–21.6						[110]
Sodium alginate		3.5				9.0–12.1			2.6–4.7			1.6–3.2	1.2–2.1								[110]
Pectin		3.5				8.5–15.3			7.6–15.2			2.2–10.3	3.0–6.7		0.7–1.9						[110]
Sodium alginate + $CaCl_2$	Poorly graded sand (SP)	2.2				5.2–7.8			4.9–8.0			5.9–7.7									[64]
Carboxymethyl cellulose	Poorly graded sand with silt (SP-SM)	1		4		3.8	3.4														[111]
Guar gum		2		3.9		4.5	4.2														[111]
Carboxymethyl cellulose		1		7.9		6.3	6														[111]
Guar gum		2		6.6		7.8	10.3														[111]
Sodium lignosulphonate	Red sand (SP)	2							11.0 [a]			10.5 a	11.0 [a]	8.5 [a]	7.5 [a]	7.5 [a]	7.0 [a]	6.5 [a]	6.5 [a]	6.0 [a]	[113]
Calcium lignosulphonate		2							11.0 [a]			10.5 a	10.5 [a]	10.0 [a]	10.0 [a]	9.5 [a]	9.0 [a]	8.5 [a]	8.0 [a]	7.5 [a]	[113]
Polyacrylamide	Red sand (SP)	2	30.0 [a]		26.0 [a]			15.0 [a]		14.5 [a]	12.0 [a]										[114]
Guar gum		2	30.0 [a]		19.0 [a]			23.0 [a]		27.0 [a]	22.5 [a]										[114]
Xanthan gum		2	30.0 [a]		13.0 [a]			12.0 [a]		10.0 [a]	8.0 [a]										[114]
Polyacrylamide	Red sand (d < 0.15)	2	30.0 [a]		27.5 [a]			22.5 [a]		19.0 [a]	15.0 [a]	15.0 [a]									[109]
Guar gum		2	30.0 [a]		26.0 [a]			20.0 [a]		14.0 [a]	14.5 [a]	14.0 [a]									[109]
Xanthan gum		2	30.0 [a]		13.5 [a]			11.5 [a]		12.0 [a]	12.5 [a]	10.5 [a]									[109]

Note. AR = application rate, SP = poorly graded sand, SP-SM = poorly graded sand with silt, a = values extracted from diagram in source.

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Appendix B

Article II: Laboratory Wind Tunnel Study

Table B.1: Results of Phase 1 wind tunnel tests. Total wind-induced soil loss after the fifth wind tunnel cycle on medium-grained sand C ($M = 2{,}645.40\,\mathrm{g/m^2}$, $SD = 783.60$) and fine-grained silica sand C ($M = 26{,}177\,\mathrm{g/m^2}$, $SD = 844.57$).

Biopolymer Concentration (wt%)	**Biopolymer**									
	CS		**CMC**		**XG**		**FBPC**		**WP**	
	Total Soil Loss (g/m²)									
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Medium-Grained Sand										
0.13 (XG = 0.05)	7.79	2.04	147.9	77.88	3.58	1.41	423.91	103.68	315.81	32.12
0.25 (XG = 0.13)	3.82	0.48	17.6	8.35	2.73	0.72	183.64	74.14	52.1	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)	18.3	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 B.2: Results of Phase 2 wind tunnel tests. Total wind-induced soil loss on medium-grained sand (Control; $M = 2{,}645.40\,\mathrm{g/m^2}$, $SD = 783.60$) and fine-grained silica sand (Control; $M = 26{,}177.49\,\mathrm{g/m^2}$, $SD = 844.57$). Samples were treated at their 'plateau concentration' based on the results of Phase 1.

Application Rate (L/m²)	Biopolymer									
	CS		CMC		XG		FBPC		WP	
	Total Soil Loss (g/m²)									
	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	10.8	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 WP = 1.25 wt%)

Table B.3: *Dust control effectiveness* (cf. Glossary) 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		WP	
	Dust Control Effectiveness (%)									
	M	SD	M	SD	M	SD	M	SD	M	SD
Medium-Grained Sand										
0.2	99.968	0.026	99.921	0.02	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	99.99	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

Table B.4: 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 cycle). 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**		**WP**	
	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	2.21	0.79	0.98	0	0.98	0
0.25 (XG = 0.13)	1.55	0.52	1.14	0.23	2.70	0.93	1.06	0.18	0.98	0
0.50 (XG = 0.25)	3.84	1.08	1.8	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
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	0.65	0.23	0.98	0.28	0.74	0.25	0.50	0
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	1.55	0.60	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 B.5: 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 cycle). Each of the three prepared samples was penetrated at the top and bottom of the centre ($n = 6$).

Application Rate (L/m²)	**Biopolymer**									
	CS		**CMC**		**XG**		**FBPC**		**WP**	
	Penetration Resistance (N)									
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Medium-Grained Sand										
0.2	1.39	0.6	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	0.98	0	0.82	0.23
0.4	0.98	0	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
Fine-Grained Silica Sand										
0.2	0.74	0.25	0.49	0	0.49	0	0.57	0.18	0.49	0
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	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

Table B.6: Compilation of results from previous studies performing wind tunnel tests. The experimental methodologies and setups 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 2.1 (cf. section 3.2.3).

Substance	Soil	D_{50} (mm)	C_u	V (m/s)	AR (L/m²)	Concentration (%)					Dust Control Effectiveness (%)					Note	Ref
						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	2	3	5	45.87	88.57	95.71	97.14	99.14	a	[110]
	SP	0.15	2.1	16.2	3.5	0.5	1	2	3	5	99.93	N/A	N/A	N/A	99.96	a	[110]
Sodium alginate	SP	0.15	2.1	16.2	1.3	0.5	1	2	3		98.84	N/A	N/A	99.99		a	[110]
	SP	0.15	2.1	16.2	3.5	0.5	1	2			99.99	N/A	99.99			a	[110]
Pectin	SP	0.15	2.1	16.2	1.3	0.5	1	2	3	5	99.99	99.99	99.99	99.99	99.99	a	[110]
	SP	0.15	2.1	16.2	3.5	0.5	1	2	3		99.99	99.99	99.99	99.99		a	[110]
Sodium alginate	SP	0.21	1.8	10	N/A	1	2				99.99	99.99				a	[142]
	SP	0.21	1.8	20	N/A	1	2				99.97	99.36				a	[142]
	SP	0.21	1.8	30	N/A	1	2				99.5	99.94				a	[142]
Pectin	SP	0.21	1.8	10	N/A	1	2				99.99	99.99				a	[142]
	SP	0.21	1.8	20	N/A	1	2				99.72	99.92				a	[142]
	SP	0.21	1.8	30	N/A	1	2				99.66	99.89				a	[142]
Acacia gum	SP	0.21	1.8	10	N/A	1	2	3			99.99	99.99				a	[142]
	SP	0.21	1.8	20	N/A	1	2	3			99.17	99.81	80			a	[142]
	SP	0.21	1.8	30	N/A	1	2	3			99.16	99.85	84			a	[142]
Xanthan gum	SP	0.13	2.1	20	1.9	0.5	1	1.5			77.08	87.5	93.75			b	[112]
	MT	0.28	9.4	20	1.9	0.5	1	1.5			78	88	92			b	[112]
	SP	0.22	7.5	20	1.9	0.5	1	1.5			76.09	89.13	91.3			b	[112]
Guar gum	SP	0.13	2.1	20	1.9	0.5	1	1.5			79.17	89.58	97.92			b	[112]
	MT	0.28	9.4	20	1.9	0.5	1	1.5			79	90	98			b	[112]
	SP	0.22	7.5	20	1.9	0.5	1	1.5			78.26	91.3	97.83			b	[112]
Carboxymethyl cellulose	SP	0.13	2.1	20	1.9	0.5	1	1.5			85.42	93.75	99.58			b	[112]
	MT	0.28	9.4	20	1.9	0.5	1	1.5			86.8	93.4	99.8			b	[112]
	SP	0.22	7.5	20	1.9	0.5	1	1.5			84.78	95.65	99.57			b	[112]
Guar gum	MT	0.15	34	17.6	1.9	0.6	1	1.6			68.7	88.7	96.52			b	[116]
Xanthan gum	MT	0.15	34	17.6	1.9	0.6	1	1.6			68.7	80.87	91.3			b	[116]

Table B.6: (continued)

Substance	Soil	D_{50} (mm)	C_u	V (m/s)	AR (L/m²)	Concentration (%)					Dust Control Effectiveness (%)					Note	Ref
						C_1	C_2	C_3	C_4	C_5	C_1	C_2	C_3	C_4	C_5		
PAM	SP [c]	N/A	< 5	20	2	0.4	0.8	1.2	1.6		98.09	99.32	99.55	99.98		b	[114]
Xanthan gum	SP [c]	N/A	< 5	20	2	0.4	0.8	1.2	1.6		88.36	97.06	99.55	99.98		b	[114]
Guar gum	SP [c]	N/A	< 5	20	2	0.4	0.8	1.2	1.6		95.69	99.43	99.55	99.98		b	[114]
Na-LS	SP [c]	N/A	< 5	20	2	2	4	6	8	10	65	89	99	99	99	b	[113]
Ca-LS	SP [c]	N/A	< 5	20	2	2	4	6	8	10	62	83	91	99	99	b	[113]
Molasses	CH	N/A	N/A	9	0.3	2	4	8	16		57.95	63.08	68.68	84.41		a	[212]
	CH	N/A	N/A	11	0.3	2	4	8	16		54.09	58.02	59.81	63.22		a	[212]
	SM	N/A	N/A	9	0.3	2	4	8	16		57.67	61.84	67.69	81.87		a	[212]
	SM	N/A	N/A	11	0.3	2	4	8	16		53.27	53.76	57.34	56.98		a	[212]
Cement	CH	N/A	N/A	9	0.3	2	4	8	16		71.7	89.49	96.35	98.46		a	[212]
	CH	N/A	N/A	11	0.3	2	4	8	16		66.97	82.04	88.24	91.07		a	[212]
	SM	N/A	N/A	9	0.3	2	4	8	16		64.39	89.72	96.71	95.92		a	[212]
	SM	N/A	N/A	11	0.3	2	4	8	16		67.1	80.21	85.22	87.77		a	[212]
Molasses + cement	CH	N/A	N/A	9	0.3	2	4	8	16		92.39	97.95	99.27	99.76		a	[212]
	CH	N/A	N/A	11	0.3	2	4	8	16		79.31	99.4	99.72	99.87		a	[212]
	SM	N/A	N/A	9	0.3	2	4	8	16		87.4	93.54	99.34	98.83		a	[212]
	SM	N/A	N/A	11	0.3	2	4	8	16		75.36	96.7	97.83	99.07		a	[212]
Hydrogel	CH	N/A	N/A	9	0.3	2	4	8	16		75.36	88.97	97.15	98.68		a	[212]
	CH	N/A	N/A	11	0.3	2	4	8	16		71.19	89.86	92.32	98.02		a	[212]
	SM	N/A	N/A	9	0.3	2	4	8	16		66.16	90.98	98.02	97.6		a	[212]
	SM	N/A	N/A	11	0.3	2	4	8	16		72.02	86.41	88.02	98.21		a	[212]

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), Abbreviations. AR = application rate, C_1-C_6 = concentrations tested in 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, V = wind velocity, LS = Lignosulphonate

Table B.7: Cont.

Substance	Soil	D_{50}	C_u	V	AR	Concentration (%)						Dust control effectiveness (%)						Note	Ref
		(mm)		(m/s)	(L/m²)	C_1	C_2	C_3	C_4	C_5	C_6	C_1	C_2	C_3	C_4	C_5	C_6		
Xanthan gum	SM	N/A	N/A	7.2	0.4	0.1						99.92						a	[143]
	SM	N/A	N/A	7.2	1	0.1						99.94						a	[143]
	SM	N/A	N/A	7.2	1.1	0.2						99.94						a	[143]
	SM	N/A	N/A	7.2	2	0.2						99.94						a	[143]
	SM	N/A	N/A	7.2	2.2	0.1						99.96						a	[143]
	SM	N/A	N/A	7.2	3.1	0.2						99.96						a	[143]
Chitosan	SM	N/A	N/A	7.2	0.5	0.1						99.28						a	[143]
Chicory vinasses	SP	0.63	2.7	13.6	1	1	2	4	6	8	10	42.98	66.15	79.3	88.1	93.33	97.29	a	[61]
Corn steep liquor	SP	0.63	2.7	13.6	1	1	2	4	6	8	10	45.2	90.26	97.94	99.62	99.78	99.68	a	[61]
Decantation Syrup	SP	0.63	2.7	13.6	1	1	2	4	6	8	10	60.09	77.41	97.98	99.56	99.41	99.44	a	[61]
Palatinose molasses	SP	0.63	2.7	13.6	1	1	2	4	6	8	10	68.55	92.19	98.98	99.57	99.59	99.53	a	[61]
Carboxmetyhl	SP-SM	0.16	2.2	14.8	1	0.3	0.5	0.7				97.8	98.3	98.71				b	[111]
cellulose	SP-SM	0.16	2.2	14.8	2	0.3	0.5	0.7				98.1	98.94	99.02				b	[111]
Guar gum	SP-SM	0.16	2.2	14.8	1	0.3	0.5	0.7				90.7	92.7	93.5				b	[111]
	SP-SM	0.16	2.2	14.8	2	0.3	0.5	0.7				90.9	93.49	97.9				b	[111]
Xanthan gum	ML	0.03	30	41.6	d	0.3	0.5	0.8				44.72	57.76	75.16				b	[118]
Carrageenan gum	ML	0.03	30	41.6	d	0.3	0.5	0.8				39.76	45.97	60.87				b	[118]
Guar gum	ML	0.03	30	41.6	d	0.3	0.5	0.8				78.89	90.07	93.16				b	[118]
Modified starches	ML	0.03	30	41.6	d	0.3	0.5	0.8				67.71	79.5	88.21				b	[118]

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), Abbreviations. AR = application rate, C_1-C_6 = concentrations tested in 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, V = wind velocity, LS = Lignosulphonate

Appendix C

Article III: Large-Scale Field Trials

Table C.1: Meteorological data measured by the weather station of the Inden open-cast lignite mine during the field trials (02 August – 21 September 2022).

Day Before/After Application	Date	Precipitation (L/m²)	Temperature (°C)			Humidity (%)	Wind (m/s)
		Total	Mean	Min	Max	Mean	Max
-6	02 Aug 22	0.0	22.6	18.5	25.6	60.4	8.7
-5	03 Aug 22	0.0	21.3	15.6	29.0	51.2	9.1
-4	04 Aug 22	0.4	29.4	19.1	33.3	41.9	7.1
-3	05 Aug 22	3.9	26.9	20.4	32.7	49.9	10.7
-2	06 Aug 22	0.0	18.4	14.6	21.9	61.8	10.9
-1	07 Aug 22	0.0	18.2	10.4	22.2	50.1	5.8
0 - Application	08 Aug 22	0.0	21.4	10.6	25.4	41.3	6.0
1	09 Aug 22	0.0	21.2	11.8	26.0	48.3	7.2
2 - Test Day 1	10 Aug 22	0.0	22.3	15.1	28.9	46.2	6.6
3	11 Aug 22	0.0	25.5	16.9	31.2	38.4	6.5
4	12 Aug 22	0.0	27.6	17.6	31.6	32.7	7.1
5	13 Aug 22	0.0	25.3	17.4	31.4	32.6	9.5
6	14 Aug 22	0.0	27.1	18.3	31.7	33.6	7.6
7	15 Aug 22	0.4	27.7	17.8	32.6	36.8	7.4
8 - Test Day 2	16 Aug 22	0.0	22.1	20.0	25.7	60.7	8.1
9	17 Aug 22	1.1	27.4	19.0	31.0	47.9	6.6
10	18 Aug 22	0.0	21.7	18.2	24.7	68.0	6.3
11	19 Aug 22	0.2	21.5	15.6	26.0	62.0	4.7
12	20 Aug 22	3.0	22.0	16.7	25.3	62.6	7.8
13	21 Aug 22	0.0	21.6	16.7	24.6	55.7	7.8
14	22 Aug 22	0.0	20.6	13.7	24.6	52.5	7.2
15 - Test Day 3	23 Aug 22	0.0	23.6	15.5	28.1	49.8	4.3
16	24 Aug 22	0.0	26.5	16.9	29.9	47.5	6.7
17	25 Aug 22	0.0	28.6	18.0	32.9	41.1	4.4
18	26 Aug 22	0.0	28.6	18.4	32.8	37.1	5.6
19	27 Aug 22	0.4	19.6	18.4	23.6	75.0	6.9
20	28 Aug 22	0.0	16.9	14.8	19.3	75.5	4.1
21	29 Aug 22	0.0	19.6	15.0	23.6	51.7	7.0
22	30 Aug 22	0.9	19.6	11.8	23.4	51.9	5.9
23	31 Aug 22	6.8	22.4	16.0	27.8	47.5	7.7

24	01 Sep 22	0.0	18.5	15.0	23.8	61.6	6.6
25 - Test Day 4	02 Sep 22	0.0	21.5	13.6	25.5	48.7	5.8
26	03 Sep 22	1.0	20.3	16.2	25.7	42.1	8.4
27	04 Sep 22	0.0	21.6	14.5	25.6	54.4	5.9
28	05 Sep 22	0.0	23.6	16.1	28.1	48.9	5.1
29	06 Sep 22	5.4	25.2	16.4	30.5	38.6	4.6
30	07 Sep 22	17.0	24.8	16.0	30.0	44.7	14.5
31	08 Sep 22	9.0	20.3	15.5	25.1	58.7	11.7
32 - Test Day 5	09 Sep 22	0.9	18.3	15.1	21.1	65.1	10.3
33	10 Sep 22	1.7	17.2	14.8	19.8	68.5	11.8
34	11 Sep 22	0.0	16.8	14.9	19.0	77.3	11.4
35	12 Sep 22	0.0	19.9	14.7	22.2	65.1	5.1
36	13 Sep 22	2.8	21.3	12.5	27.1	52.1	4.3
37	14 Sep 22	6.0	21.9	17.3	25.7	57.4	5.1
38 - Test Day 6	15 Sep 22	2.7	15.1	13.2	18.1	79.9	4.9
39	16 Sep 22	1.6	15.2	12.5	17.6	70.3	5.6
40	17 Sep 22	4.8	12.4	9.3	14.6	74.7	10.8
41	18 Sep 22	10.5	12.4	9.3	14.7	69.9	9.9
42	19 Sep 22	0.2	10.0	8.4	12.5	79.3	12.8
43	20 Sep 22	0.2	14.2	8.9	16.7	67.5	8.3
44	21 Sep 22	0.0	13.5	9.7	15.5	68.4	6.4
45 - Test Day 7	22 Sep 22	0.0	14.2	6.8	17.7	59.6	4.6

Table C.2: Results of dust emission measurements performed at velocity $v_1 = 13.3\,\mathrm{m/s}$, including the results of the background load tests.

Day	Biopolymer						Control		Background Load	
	CS		FBPC		XG		C			
	M	SD	M	SD	M	SD	M	SD	M	SD
	TSP (mg/m³)									
2	0.08	0.03	0.21	0.17	0.09	0.03	31.23	12.71	0.03	0
8	0.05	0	0.08	0.02	0.07	0.01	4.50	1.35	0.03	0.01
15	4.91	6.36	15.12	4.82	2.93	3.18	14.34	7.32	0.02	0.01
25	52.43	30.07	18.80	2.11	52.47	22.46	44.47	10.73	0.04	0.03
32	0.28	0.20	2.22	0.20	0.20	0.13	3.12	0.80	0.02	0
38	0.05	0.02	0.02	0.01	0.02	0.01	0.04	0.03	0.03	0.01
45	0.75	0.22	9.18	2.94	0.79	0.53	31.03	4.11	0.05	0
	PM_{10} (mg/m³)									
2	0.06	0.01	0.14	0.09	0.07	0.03	30.33	12.29	0.02	0
8	0.04	0	0.07	0.02	0.05	0	3.49	1.15	0.03	0.01
15	4.61	5.93	14.5	4.78	2.79	3.04	14.04	7.12	0.02	0.01
25	50.8	29.19	17.87	2.30	50.93	22.22	43.47	10.38	0.04	0.02
32	0.24	0.18	2.08	0.20	0.16	0.12	2.93	0.71	0.02	0
38	0.04	0.01	0.01	0.01	0.02	0.01	0.04	0.02	0.03	0
45	0.70	0.20	8.94	2.86	0.75	0.50	30.50	4.08	0.04	0
	$PM_{2.5}$ (mg/m³)									
2	0.02	0	0.04	0.02	0.03	0.02	29.37	11.91	0.02	0
8	0.03	0	0.04	0.01	0.03	0	1.85	0.69	0.02	0
15	4.41	5.65	14.01	4.80	2.67	2.97	13.81	6.95	0.01	0
25	49.9	28.69	17.13	2.46	49.97	22.06	42.73	10.18	0.02	0.01
32	0.21	0.16	2.02	0.20	0.13	0.12	2.82	0.64	0.01	0
38	0.03	0.01	0.01	0.01	0.02	0.01	0.03	0.02	0.03	0
45	0.66	0.19	8.84	2.84	0.72	0.47	30.1	4.01	0.03	0

Table C.3: Results of dust emission measurements performed at velocity $v_2 = 15.5\,\mathrm{m/s}$.

Day	Biopolymer						Control	
	CS		FBPC		XG		C	
	M	SD	M	SD	M	SD	M	SD
	TSP (mg/m^3)							
2	0.22	0.20	0.27	0.12	0.07	0.04	39.20	16.19
8	0.09	0.02	0.09	0.01	0.11	0.02	5.45	1.72
15	1.25	0.58	13.5	2.33	2.77	1.04	24.83	3.62
25	31.07	2.89	14.47	1.58	19.83	3.73	39.07	23.39
32	0.55	0.23	2.46	1.25	0.19	0.12	8.27	5.11
38	0.12	0.06	0.02	0.01	0.01	0	0	0
45	0.59	0.17	13.67	5.54	1.10	0.55	21.13	4.83
	PM_{10} (mg/m^3)							
2	0.15	0.14	0.18	0.08	0.05	0.03	38.4	16.01
8	0.08	0.02	0.07	0.01	0.09	0.02	4.09	1.29
15	1.25	0.58	13.00	2.33	2.61	0.92	24.37	3.58
25	30.2	2.73	13.73	1.65	19.10	3.68	38.23	23.15
32	0.49	0.22	2.35	1.20	0.18	0.11	7.99	5.11
38	0.10	0.05	0.02	0.01	0.01	0	0	0
45	0.54	0.15	13.38	5.46	1.04	0.53	20.8	4.81
	$PM_{2.5}$ (mg/m^3)							
2	0.05	0.04	0.09	0.05	0.03	0.01	37.43	15.80
8	0.06	0.02	0.05	0	0.06	0.02	2.23	0.71
15	1.25	0.58	12.59	2.29	2.47	0.83	24.07	3.50
25	29.57	2.58	13.00	1.85	18.77	3.63	37.58	22.96
32	0.46	0.22	2.28	1.19	0.16	0.11	7.79	5.13
38	0.09	0.04	0.02	0.01	0.01	0	0	0
45	0.51	0.15	13.19	5.39	0.98	0.51	20.53	4.76

Table C.4: Results of dust emission measurements performed at velocity $v_3 = 17.4\,\mathrm{m/s}$.

Day	Biopolymer						Control	
	CS		FBPC		XG		C	
	M	SD	M	SD	M	SD	M	SD
	TSP (mg/m³)							
2	0.06	0.01	0.22	0.05	0.05	0.02	22.83	10.04
8	0.08	0.01	0.12	0.03	0.12	0.04	7.16	1.43
15	1.1	0.52	7.42	1.74	64.00	11.87	12.2	10.48
25	25.33	7.67	14.43	1.54	37.73	5.28	39.2	2.36
32	0.55	0.33	2.46	0.91	0.2	0.16	4.48	5.14
38	0.08	0	0.01	0	0.02	0	0.04	0.02
45	0.86	0.4	8.93	2.8	5.50	1.79	28.23	3.51
	PM_{10} (mg/m³)							
2	0.05	0.01	0.16	0.04	0.04	0.01	22.13	9.97
8	0.07	0	0.1	0.02	0.1	0.03	5.74	1.20
15	1.10	0.52	6.75	2.11	62.83	11.65	11.97	10.22
25	24.9	7.43	13.87	1.44	36.8	5.27	37.83	2.27
32	0.50	0.31	2.31	0.84	0.17	0.13	4.34	4.95
38	0.06	0	0.01	0	0.02	0	0.04	0.02
45	0.81	0.38	8.81	2.79	5.30	1.74	27.83	3.59
	$PM_{2.5}$ (mg/m³)							
2	0.02	0.01	0.08	0.03	0.02	0	21.37	9.86
8	0.04	0	0.07	0.01	0.07	0.02	3.69	0.81
15	1.10	0.52	5.90	2.82	61.93	11.56	11.77	10.01
25	24.57	7.27	13.5	1.39	36.17	5.15	36.57	2.18
32	0.48	0.30	2.2	0.78	0.15	0.12	4.3	4.91
38	0.05	0.01	0.01	0	0.02	0	0.04	0.02
45	0.77	0.39	8.71	2.78	5.15	1.69	27.43	3.66

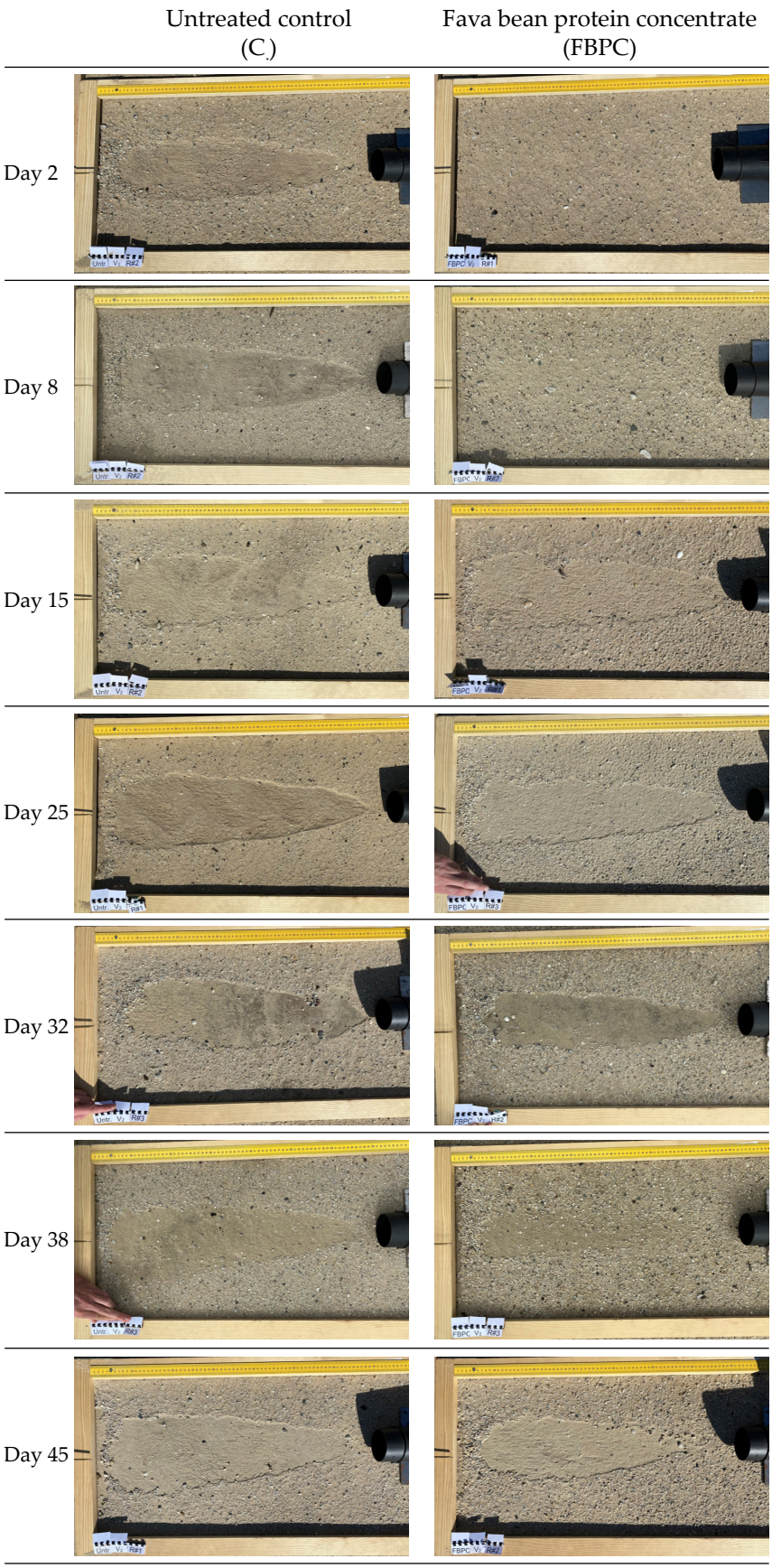

Figure C.1: Exemplary photographs of plots on the untreated and FBPC-treated trial areas after subjecting them to air speed of $v_2 = 15.5\,\mathrm{m/s}$ for 60 s. The trial plots had dimensions of $40 \times 70\,\mathrm{cm}$.

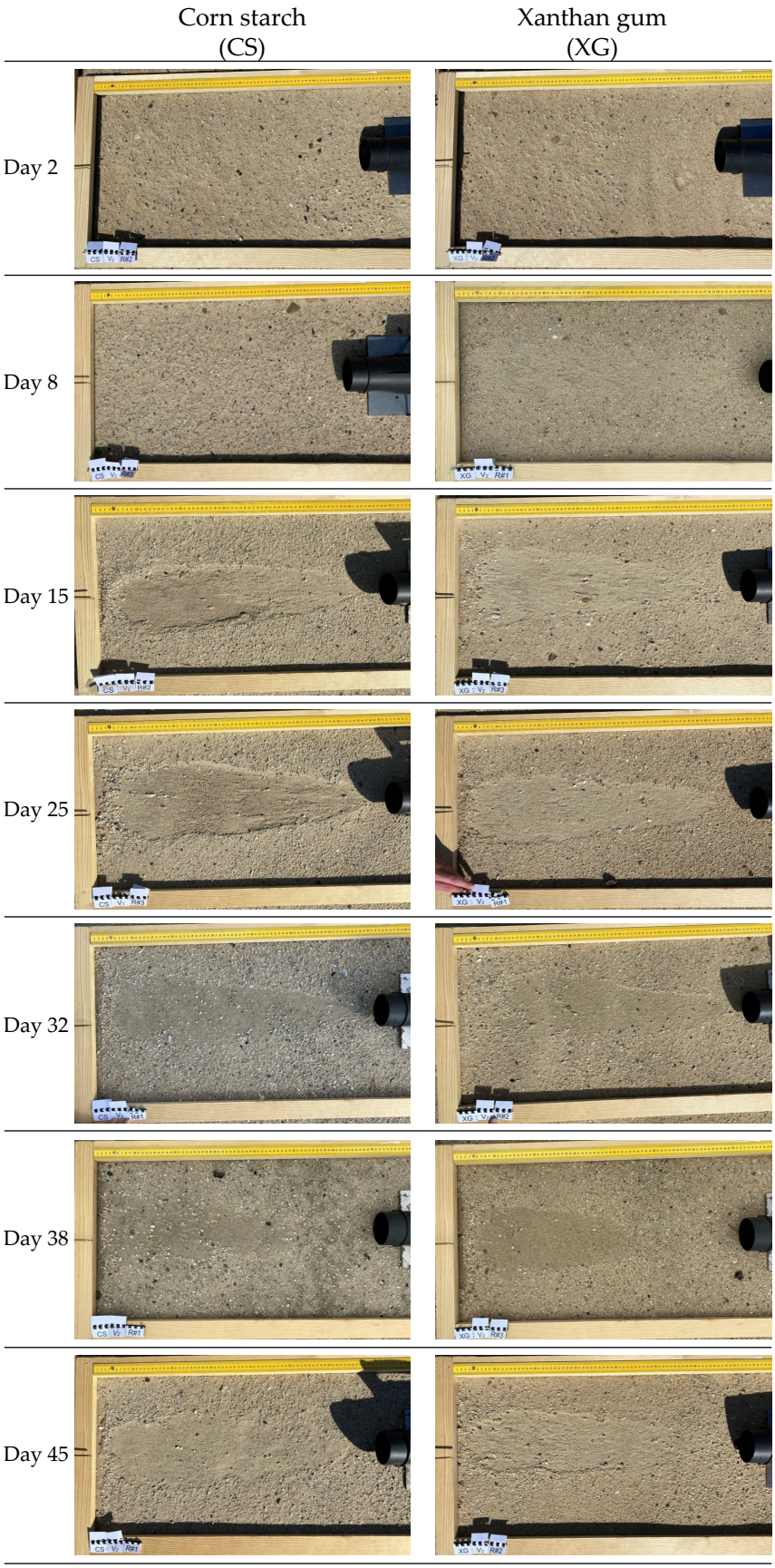

Figure C.2: Exemplary photographs of CS- and XG-treated trial plots after subjecting them to air speed of $v_2 = 15.5\,\mathrm{m/s}$ for 60 s. The trial plots had dimensions of $40 \times 70\,\mathrm{cm}$.

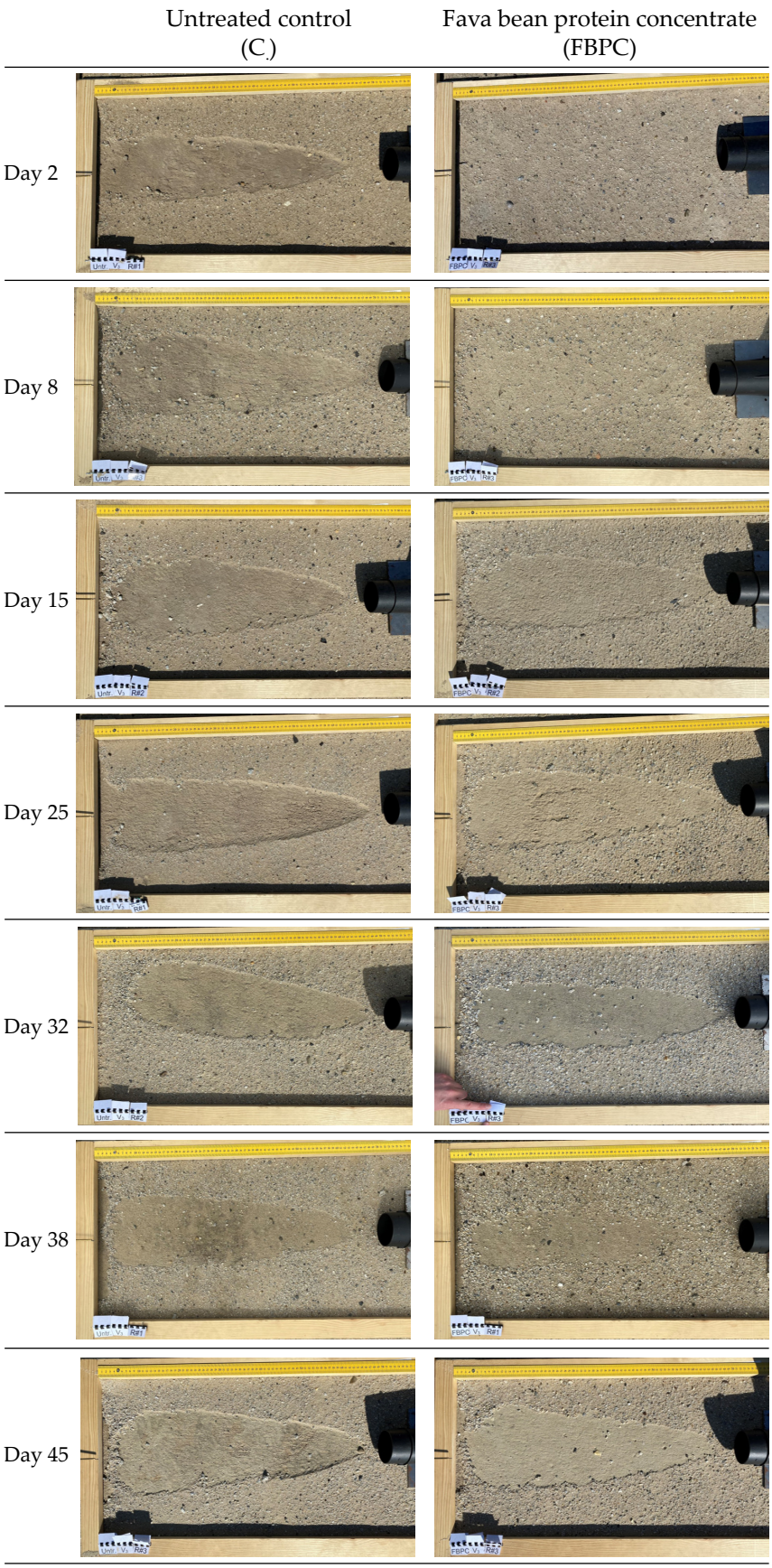

Figure C.3: Exemplary photographs of plots on the untreated and FBPC-treated trial areas after subjecting them to air speed of $v_3 = 17.4\,\mathrm{m/s}$ for 60 s. The trial plots had dimensions of $40 \times 70\,\mathrm{cm}$.

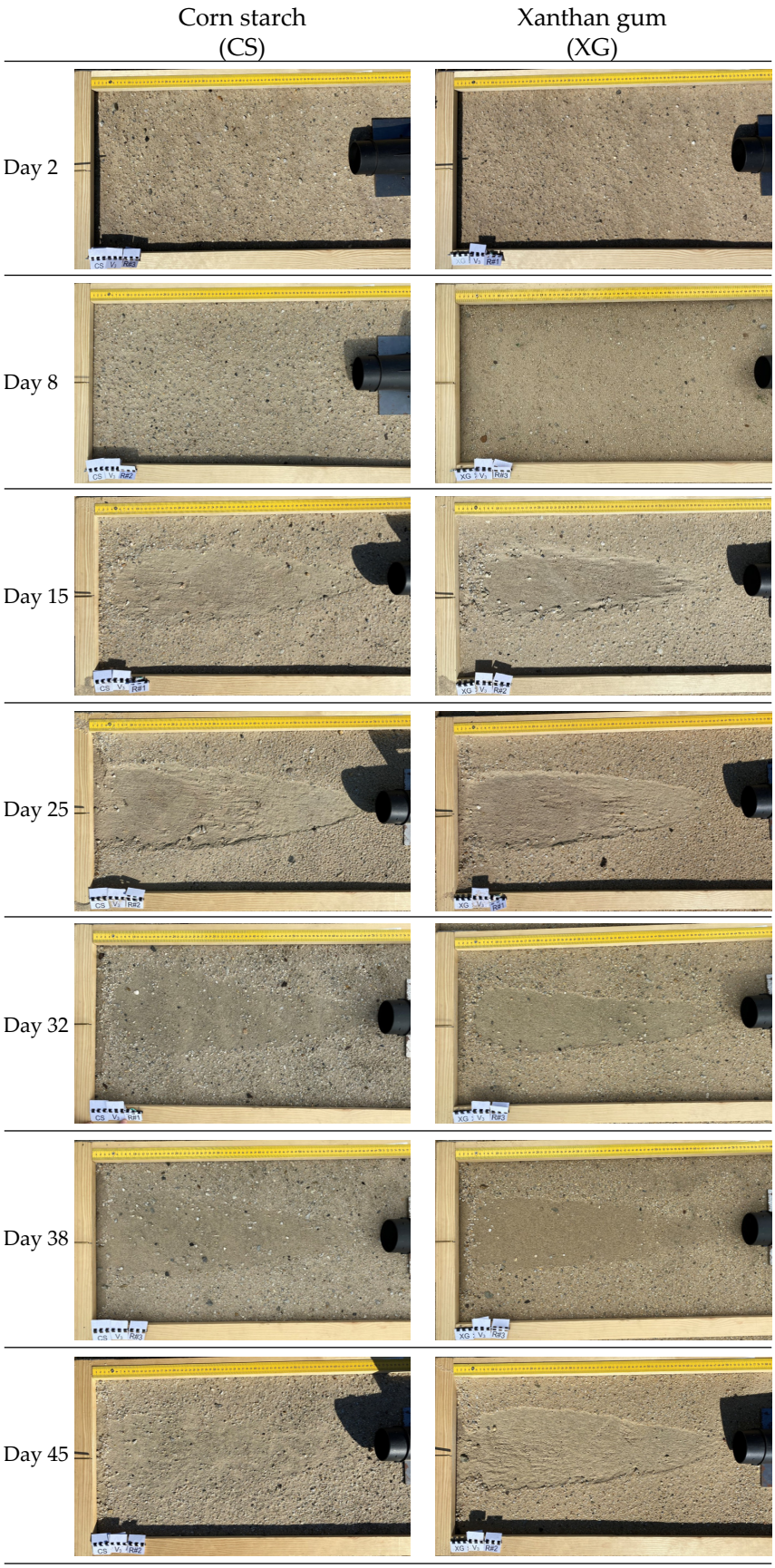

Figure C.4: Exemplary photographs of CS- and XG-treated trial plots after subjecting them to air speed of $v_3 = 17.4\,\mathrm{m/s}$ for 60 s. The trial plots had dimensions of $40 \times 70\,\mathrm{cm}$.

Table C.5: Results of the penetrometer tests conducted on the trial areas treated with CS, FBPC, XG and the untreated control area. Tests were performed with twenty replicates ($n = 20$).

Day	Biopolymer						Control	
	CS		FBPC		XG		C	
	M	SD	M	SD	M	SD	M	SD
	Penetration Resistance (N)							
2	20.26	13.59	17.56	11.93	8.63	5.05	3.63	8.87
8	19.23	5.62	18.88	5.82	6.67	6.37	3.58	4.31
15	2.11	1.36	9.81	5.9	4.71	2.97	3.24	3.84
25	2.84	0.98	8.98	4.35	3.04	1.45	5.20	1.78
32	4.76	1.40	8.73	2.48	5.05	1.25	4.46	1.33
38	7.31	2.60	8.24	3.60	5.35	2.43	6.72	2.91
45	8.49	3.71	6.62	3.02	6.18	4.00	5.20	6.04

Table C.6: Compilation of previous field trials testing the application of dust suppressants on exposed, undisturbed soils.

Substances	C (%)	AR (L/m^2)	Test Field	Dur.	Conclusion	Note	Ref
Dust Fygther (pulp proc. by-product)	25	0.8	Soil: Tailings Site: TSF Size: 2.5 × 16 m	4 m	• Averaged over study, the mean emission rates of all test plots (incl. suppressants and control) were similar high and showed high variability.	a, b, c, e	[121]
Entac (pulp proc. by-product)	20	1.4			• No clear effect of the dust suppressants	a, b, d	[121]
EcoAnchor (acrylic polymer)	11	10			• Field site conditions, particularly rainfall, significantly influenced study results	a, b, c	[121]
Soil Sement (acrylic polymer)	10	1				a, b, c	[121]
Tall oil pitch	20	2	Soil: Sandy loam Size: 16 × 16 m	14 m	• Significant reduction in PM_{10} emissions for first 3–6 months	c	[228]
	17	2			• After 6 months protective crust started to decompose	c	[228]
	14	2				c	[228]
Chicory vinasses	10	1.5		1 m	• Considerable short-term reduction in dust emissions until D14	c, e	[62]
Corn steep liquor	5	0.8	Soil: SP Size: 0.4 × 0.7 m			c, e	[62]
Decantation syrup	6	1			• Rainfall as main impairing factor	c, e	[62]
Palatinose molasses	6	1				c, e	[62]
Poloxamer	5.6	N/A	Soil: Tailings Site: TSF beach Size: N/A	2 w	• TSF beach: Reduction in PM_{10} by 50% in week 1, and almost no effect in week 2 • TSF slope: Reduction in PM_{10} by 73% in week 1, and almost no effect in week 2 • Rainfall likely main impairing factor	c, e	[140]
Poloxamer	5.6	18.5	Soil: Tailings Site: TSF slope Size: 36 × 6 m		• Moisture retention main mechanism	c, e	[140]
Starch + polyacrylamide (10:1)	0.7, 1.0, 1.3	5 × 0.67 kg/m^2	Soil: Loess Size: N/A	1 m	• One-month effective dust suppression • Aggregation and crust formation as main mechanisms	c, d, e	[167]

Note. AR = application rate, C = concentration, Dur. = duration, m = month, N/A = not available, Ref = reference, TSF = tailings storage facility, w = week, a = product dosage (dry matter of substance unknown), b = deliberately induced physical disturbance by skid steer track after third test day, c = substance applied by a single application, d = substance applied in 3 coats, each 20 min apart, d = application regime not clearly explained in the source. It is assumed that the suppressant was applied over five days, each day at 0.67 kg/m^2, e = tests performed with portable in situ soil wind erosion laboratory (PI-SWERL).

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Glossary

Aerodynamic diameter is the diameter of a unit-density sphere with the same aerodynamic properties as the particle in question. This means that particles of any shape or density will have the same aerodynamic diameter if their settling velocity is the same [305].

Aerodynamic entrainment is a dust generation mechanism by which dust particles are lifted from the surface by aerodynamic forces. The contribution of this mechanism to the total dust emissions is assumed to be small due to the diminishing importance of gravity and aerodynamic forces for dust-sized particles.[44]

Anthropogenic dust comprises any dust generated by human-induced mechanical or explosive disturbance or wind erosion from barren human-disturbed surfaces [42].

Application rate refers to the rate of application at which a dust suppressant is sprayed on the soil to be treated (typically given in L/m^2).

Barren area is an area with no, or only very scarce, vegetative cover.

Biodegradability is the ability of organic matter to be broken down by biotic (microbial enzymes) and abiotic (e.g., oxidation, photodegradation, and hydrolysis) processes [252, 253].

Biopolymers are biodegradable polymers produced by biological organisms - plants, animals, and bacteria - and based on their composing monomers can be categorised into polysaccharides, proteins, and polynucleotides [69]. Polysaccharides and proteins are the most relevant biopolymer categories for any industrial and commercial products [77].

Concentration is the concentration of a dust suppressant treatment, which is typically given in wt%.

Creep is the wind erosion mechanism by which large particles (typically 0.5 to 1 mm diameter), which are usually too heavy to be lifted from the soil by aerodynamic forces, creep or roll along the soil surface propelled by the wind forces [16].

Disaggregation is the dust generation mechanism where saltating aggregates, consisting of dust and sand particles, disaggregate on impact with the soil, resulting in dust emissions. Under natural conditions dust particles typically exist as dustcoats attached to sand particles or as aggregates in clay-containing soils.[44]

Dosage refers to the dry substance of dust suppressant applied per unit of area (g/m^2) on a soil to be treated. The dosage is the product of the application rate and concentration.

Durability is the ability of something to remain intact or functional over time [306]. In the context of research on dust suppressants, it refers to the ability of dust suppressant treatments to remain intact when exposed to anthropogenic and environmental influences (e.g., rainfall, biodegradation, or mechanical disturbance).

Dust can be defined as a heterogeneous mixture of particulate matter, which is or can be suspended into the atmosphere as a result of mechanical, explosive or windblown suspension of organic (e.g., flour, wood, pollen), synthetic (e.g., tyre abrasion), or mineral solids (minerals and metals), with the exclusion of particulate matter generated by internal or external combustion processes [42]. Particles between 60 and 2,000 μm diameter can mostly only be suspended in the air for a short period, and only particles $\leq 60\,\mu$m are typically classified as dust [44]. Shao et al. [44] distinguished between three dust generation mechanisms: *Aerodynamic entrainment*, *saltation bombardment*, and *disaggregation*. Definitions for these mechanisms can also be found in this Glossary.

Dust control effectiveness is a performance indicator commonly used in wind tunnel studies (see 3.4.1 and Table B.3) for quantifying the *effectiveness* (cf. definition below) of a dust suppressant treatment relative to an untreated or water-treated control in % (cf. Equation 3.1).

Dust suppressant also referred to as dust palliatives, surfactants or dust control products, are substances used to control particulate matter emissions from trafficked soil surfaces, such as unpaved haul roads or non-trafficed, undisturbed, barren areas prone to wind erosion [14, 48].

Ecotoxcicity can be defined as as the potential of biological, chemical, or physical stressors to affect ecosystems. Such stressors might occur in the natural environment at densities, concentrations or levels high enough to disrupt the natural biochemistry, physiology, behaviour and interactions of the living organisms that comprise the ecosystem.[248, 307]

Effective is generally defined as the capacity of something to produce an intended result [306]. In the context of this thesis, it refers to the ability of a biopolymer treatment to increase specific soil parameters relevant to their functional potential as dust suppressants. A biopolymer treatment is deemed *effective* if it improves the relevant parameters tested compared to water or untreated controls. The definition of *effectiveness* can be found below.

Effectiveness is generally defined as the degree to which something is *effective* [306]. Article I examined the *effectiveness* of biopolymer treatments in improving specific soil properties indicative of their functional potential as dust suppressants (i.e., penetration resistance (N), moisture retention (%) and crust thickness (mm). The higher these parameters are relative to water-treated control samples, the greater the *effectiveness* of the treatment. For Article II, the *effectiveness* of the biopolymer treatments on wind erosion resistance was measured directly. The lower the airflow-induced soil loss (g/m^2) compared to an untreated sample, the higher the *effectiveness* of the treatment. Finally, Article III directly investigated the *effectiveness* of the biopolymer treatments in suppressing airflow-induced dust emissions (TSP, PM_{10} and $PM_{2.5}$, in mg/m^3) relative to untreated trial plots. The lower the airflow-induced dust emissions, the higher the *effectiveness* of the treatments.

Emission is generally defined as the act of sending out gas, heat, light, noise, vibration, particulates, etc., into the atmosphere [306]. In the context of this thesis it primarily refers to the suspension of dust particles into the atmosphere as dust emissions.

Exposed area see barren area.

Fugitive dust is defined as any particulate matter that could not reasonably pass through a stack, chimney, vent, or other opening with an equivalent function [308]. Fugitive dust sources are either *process sources* or *open dust sources* [42]. *Open dust sources* are all non-ducted particulate matter emissions generated by mechanical or wind forces acting on material, such as loading, dumping, bulk material handling systems, haulage on unpaved

haul roads, blasting, or wind erosion from exposed surfaces, such as stockpiles, working benches, slopes, overburden and waste dumps, or tailings dams and beaches. *Process sources* are associated with industrial processes, such as rock crushing. [42]

Inhalable dust refers to dust particles $< 100\,\mu$m (typically between 5 and $10\,\mu$m) that can be inhaled through the nose and mouth, and can enter and deposit in the respiratory tract [13].

Mine dust is in the context of this thesis defined as the entirety of anthropogenic dust emissions generated at mine sites. Mine dust is predominantly composed of mineral dust (mineral solids) but inevitably contains small fractions of organic and synthetic constituents (e.g., tyre abrasion). While most dust emissions at mine sites originate from the operation itself, they may also include resuspended dust that initially stems from the surroundings of the sites. The composition of the mineral solid fraction of mine dust depends on the mineralogy of the material being extracted.

Mine soil can be defined as soil that has been disturbed by mining activities. This includes any soil that has been removed, exposed, processed, and dumped or discharged in order to extract ore. Mine soils often have poor organic matter and nutrients and may be acidic, alkaline, or contaminated with pollutants. This often makes it challenging to cultivate a vegetative cover, causing mine soils to be highly susceptible to wind erosion.[309]

Mix-in application refers to the process of mixing a soil stabilising agent or dust suppressant into the soil. It encompasses multiple work steps by a grader (or recycler), including scarifying, blading, suppressant application, soil mixing, shaping and compacting [48].

Nuisance dust includes all dust particles typically not associated with adverse health effects [310], and only negative aesthetic effects, and typically ranges from 0.001 to $50\,\mu$m in size. This type of dust is rather a nuisance for employees and host communities, as it settles on the homes and properties. It does typically not remain suspended in the air for long periods, as it settles due to the gravitational forces. [5]

Particulate Matter (PM) refers to the dust fractions PM_{10} and $PM_{2.5}$, which include all particles ≤ 10 and $2.5\,\mu$m, respectively. Their concentration is typically measured in mg/m³.

Plateau concentration in the context of the laboratory wind tunnel study (Article II), refers to the treatment concentration beyond which further increasing the concentration results in only a marginal further reduction in the wind-induced soil loss experienced by a biopolymer-treated soil sample throughout wind tunnel testing.

Polynucleotides are a biopolymer category comprised of nucleotides. DNA and RNA are its most popular representatives [77].

Polysaccharides are are a biopolymer category that comprises polymeric carbohydrates that are composed of hundreds to thousands repeating saccharide units linked by glycosidic bonds. They are derived from plant cell walls, seeds, grains, tree exudates, algae, bacterial fermentation, and partially animal sources. Cellulose derivatives (cell walls in green plants, such as trees) and starches count to the most abundant and relevant polysaccharides on the globe [77].

Proteins are a biopolymer category that comprises polypeptides composed of repeating amino acid units linked by peptide bonds. They are derived from animal (e.g., milk, meat, egg, and gelatine) and botanical sources (e.g., wheat, beans, potato, soy, and pea).

Respirable dust refers to dust particles, typically $< 10\,\mu$m that can reach the respiratory bronchioles, deposit in the lungs' gas exchange regions (alveolar regions), and absorb trace elements into the bloodstream. [5, 13, 310]

Saltation is the wind erosion mechanism by which particles (typically 0.1–0.5 mm) are either detached from the soil surface by wind forces or dislodged by other saltating particles and bounce along the soil surface but are typically too large to be dispersed into the atmosphere [43]. This can create an 'avalanching' or 'cascading' effect, where a few saltating particles inflict the dislodgement and saltation of many more particles, resulting in saltation to also having an abrasive effect on the soil surface.

Saltation bombardment describes the dust generation mechanism by which the impact force of saltating particles on a soil surface overcomes the inter-particle cohesion that holds dust particles to the soil surface, resulting in dust emission.[44]

Soil stabilisation is a collective term for any physical, chemical, mechanical, biological, or combined method employed to improve certain properties of natural soils to achieve certain desired engineering purpose [311]. Chemical and biological methods involve the conditioning of the soil using soil stabilising agents (soil stabilisers), which are mixed-in into the soils and typically used for different earthwork systems, such as hydraulic barriers, retaining walls, foundation and excavation support, liquefaction mitigation environmental remediation or the stabilisation of unpaved roads [312]. Chemical stabilisers, such as mud, gypsum, bitumen, ashes, fibres, slags, or lime have been used by humans since ancient times and act either by cementation or ion-exchange reactions [79, 311]. Since the early 20^{th} century cement and lime emerged to the most commonly used stabilisers for ground improvement [313], but their usage is subject to growing concerns due to its associated climate change impacts [73].

Soil texture refers to the proportions of gravel, sand, silt, clay, and organic matter in a soil.

Spray-on application refers to the topical application of dust suppressants by simply spraying the suppressant by water trucks equipped with spray bars or other pieces of equipment on the ground to be treated.

Suspension is the wind erosion mechanism by which the suspended particles (generally $<$ 0.1 mm) are primarily generated by saltating particles that abrade larger particles like sandblasting. Suspension is the floating motion of dust-sized particles in the atmosphere [44].

Thoracic dust refers to the dust fraction typically $< 25\,\mu$m that can enter the respiratory tract, pass through the trachea and deposit in the lung airways or the gas exchange region. [13]

Total suspended particles (TSP) comprises all suspended particles, generally ranging between 0.001 and 100 μm in aerodynamic diameter. The TSP concentration is typically measured in mg/m^3.

Undisturbed area is in the context of this thesis defined as an area which is not, or only very rarely, subject to vehicular traffic or other types of mechanical disturbance.

Untrafficked area see undisturbed area.

Wind erosion resistance refers to the resistance of a soil surface to resist wind erosion under certain windflow conditions.

Wind ersoion is the process of particle entrainment, transport and deposition by wind [43]. Entrainment (detachment) of particles occurs when the aerodynamic drag and lift forces (i.e., the friction velocity) of the wind acting on a soil surface exceed the gravitational and inter-particle cohesion forces resisting particle removal (i.e., the threshold friction velocity of a soil matrix) [44]. It is distinguished between the wind erosion mechanisms: *Suspension*, *Creep*, and *Saltation*. Definitions for these mechanisms can also be found in this Glossary.

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Publications and Presentations Not Related to This Thesis

Peer-Reviewed Articles:

Freer, J., Lübeck, M., **Sieger, J.L.**, Lottermoser, B.G. and Braun, M. Effectiveness of food processing by-products as dust suppressants for exposed mine soils: results from laboratory experiments and field trials. In: *Appl. Sci.* 12.22 (2022), p. 11551, Doi:10.3390/app122211551.

Freer, J., **Sieger, J.L.**, Lottermoser, B.G. and Braun, M. Effectiveness of food processing by-products in suppressing wind-induced dust emissions from mine soils: results from laboratory wind tunnel experiments. In: *SSRN Electronic Journal.* (2022), Doi:10.2139/ssrn.4220674.

Conference Proceedings and Presentations:

Lee, H.J., Krishnan, A., Brell-Cokcan, S., Knußmann, J., Brochhaus, M., Schmitt, R.H., Emontsbotz, J.J. and **Sieger, J.L**. Importance of a 5G network for construction sites: limitation of WLAN in 3D sensing applications. In: *Proceedings of the 39th International Symposium on Automation and Robotics in Construction.* Ed. by T. Linner, B. García de Soto, R. Hu, , et al. Bogotá: International Association for Automation and Robotics in Construction, 2022.

Freer, J., Futschek, F. and **Sieger, J.L.**. Aqueous surfactant solutions for dust suppression in open pit mines: the influence of different soil textures on wettability. In: *Aachen International Mining Symposia, Abstract volume: First International Conference Mineral Resources for Future Generations.* Ed. by B. G. Lottermoser. Aachen: RWTH Aachen University, 2020.

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Supplementary Material

The supplementary material of this thesis contains the numerical raw data, the processed data, and photographs documenting the sample preparation and test work carried out for each of the three study phases. It is stored on the attached CD in the format of .xlsx, .jpeg and .png files.