Potential von Abfall- und Nebenprodukten der Lebensmittelverarbeitung als Staubbindemittel auf exponierten Grubenböden

Potential of Food Processing Wastes and By-Products as Dust Suppressants on Exposed Mine Soils

Von der Fakultät für Georessourcen und Materialtechnik der
Rheinisch-Westfälischen Technischen Hochschule Aachen

zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften

genehmigte Dissertation

vorgelegt von

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Tag der mündlichen Prüfung: 01.06.2026

Diese Dissertation ist auf den Internetseiten der Universitätsbibliothek online verfügbar.

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Acknowledgements

First and foremost, I would like to express my deepest gratitude to my doctoral supervisors, *Univ.-Prof. Dipl.-Sc. Ph.D. Bernd Lottermoser* and *Univ.-Prof. Dipl.-Ing. Dr. mont. Nikolaus Sifferlinger*. Their support was instrumental in making this thesis possible.

Special thanks to my former colleague and dear friend, *Dr. Johannes Sieger*, who not only shares my passion in this research area, but has also provided invaluable advice and encouragement throughout my doctoral journey. I am particularly grateful for his invaluable collaboration as co-author on two of the three dissertation publications.

I extend my appreciation to *Marius Braun* and *Dr. Rudolf Suppes* for their significant contributions during the formative phase of my doctorate. Their insightful discussions and feedback were crucial in shaping my doctoral concept. I am particularly grateful for *Marius Braun's* invaluable collaboration as co-author on all three dissertation publications.

My sincere thanks to *Devrim Gürsel*, *Dr. Stephanie Lohmeier*, *Dr. Martin Knippertz*, and *Dr. Philipp Schulte* for their support in soil characterization. I also thank the master students, *Bernd Müller*, *Peter Bucher* and *Maximilian Lübeck*, who helped me prepare and conduct some of the experimental work.

I gratefully acknowledge *RWE Power AG* for facilitating field trials at the Inden open-pit lignite mine. In particular, I thank *Klaus Gödde*, *Dennis-Marc Schier* and *Eva Thelen*, whose support and cooperation were vital to the project's success.

Finally, I owe my deepest gratitude to my beloved *family* and *friends* for their unconditional support, patience and encouragement. Their belief in me has been a constant source of strength throughout this challenging but rewarding journey.

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German Abstract

In Tagebauen und Aufbereitungsbetrieben führt Winderosion auf exponierten Böden zur Freisetzung erheblicher Mengen mineralischen Staubs. Staubbindemittel haben sich als wirksam zur Reduzierung dieser Emissionen erwiesen, jedoch weisen sowohl konventionelle Optionen (z. B. Bewässerung und synthetische Polymere) als auch biobasierte Alternativen (z. B. Biopolymere) Nachteile auf. Dazu zählen hohe Produktpreise, ein erheblicher Wasserverbrauch, große CO_2-Fußabdrücke, potenzielle Schäden an Ökosystemen sowie eine schwierige Handhabung.

Die Verwendung von Abfall- und Nebenprodukten der Lebensmittelverarbeitung (ANL) stellt eine umweltfreundliche Lösung zur Staubunterdrückung dar, die kosteneffizient und einfach in der Anwendung ist. ANL sind biologisch abbaubar, lösen sich leicht in kaltem Wasser, ohne die Viskosität zu verändern, sind kostengünstig zu beziehen und bestehen aus Kohlenhydraten und Proteinen, die sich als wirksam gegen Winderosion erwiesen haben. Trotz ihres vielversprechenden Potentials als Staubbindemittel haben ANL bislang wenig Aufmerksamkeit in der Forschung erhalten. Die vorliegende Dissertation verfolgt das Ziel, diese Forschungslücke zu schließen, indem das Potential von ANL zur Reduzierung von Staubemissionen, welche infolge von Winderosion auf exponierten Grubenböden entstehen, untersucht wird. Die Forschungsarbeit gliedert sich in drei Studien, deren Ergebnisse in jeweils einer Publikation veröffentlicht wurden.

Die erste Studie (S. 41 ff.) analysierte die einaxiale Druckfestigkeit und hatte zum Ziel, die Fähigkeit von ANL, Bodenpartikel zu agglomerieren, zu bewerten. Diese stellt einen wichtigen Mechanismus zur Staubunterdrückung dar. Es wurden 16 ANL in Konzentrationen von 2 % und 4 % auf mittel- bis grobkörnigem Sand getestet, dem gleichen Substrat, das ebenso in den Experimenten der Studien zwei und drei verwendet wurde. Die Ergebnisse zeigten, dass eine Zugabe von ANL die mechanische Festigkeit des Bodens signifikant erhöhte. Während der unbehandelte Boden eine einaxiale Druckfestigkeit von lediglich 11 kPa aufwies, erreichten die wirksamsten ANL Festigkeiten im Bereich von 1.366 bis 2.026 kPa, wobei eine Substanz sogar 7.535 kPa erreichte. Die ermittelten einaxialen Druckfestigkeiten entsprechen damit weitgehend den in der Literatur für kommerzielle Biopolymere dokumentierten Werten und übertreffen diese in einzelnen Fällen. Eine weiterführende Analyse ergab, dass ANL mit einem hohen Gehalt an Proteinen und Polysacchariden tendenziell größere Festigkeitssteigerungen bewirkten als solche, die überwiegend aus niedermolekularen Kohlenhydraten bestehen.

Da die einaxiale Druckfestigkeit nur indirekte Rückschlüsse auf die Wirksamkeit von Stoffen zur Verminderung von Winderosion geben kann, wurde mit der zweiten Studie (S. 63 ff.) untersucht, inwiefern ANL die Bodenoberfläche so modifizieren können, dass deren Erosionsbeständigkeit steigt. Hierzu wurden in Laborwindkanalversuchen (13,57 m/s) vier ANL mit variierenden Konzentrationen (1–10 %) und Auftrags-

mengen (0,25–3 l/m²) getestet. Die Ergebnisse zeigten, dass eine Auftragung von ANL den Bodenverlust signifikant verringerte. Jeder der untersuchten Stoffe reduzierte den Bodenverlust um mehr als 99 %. Demgegenüber bewirkte die Anwendung von Wasser lediglich eine Reduktion des Bodenverlusts von unter 39 %. Die Daten legten zudem dar, dass für jeden Stoff eine optimale Konzentration und Auftragsmenge (5–10 %; 0,75–1,5 l/m²) existiert. Eine Überschreitung dieser Schwellenwerte führte zu keiner oder einer vernachlässigbaren Verbesserung der Wirksamkeit.

Die dritte Studie (S. 79 ff.) analysierte die Auswirkungen von Umwelteinflüssen auf die Wirksamkeit von ANL bei der Bildung winderosionsbeständiger Bodenoberflächen, da diese die Langlebigkeit von Staubbindemitteln maßgeblich beeinträchtigen können. Hierzu wurden zunächst vier ANL in Auslaugungsversuchen sich wiederholenden Nass-Trocken-Zyklen und variierenden Niederschlagsintensitäten (0,25–4 l/m²) ausgesetzt. Anschließend folgte eine Exposition gegenüber winderodierenden Kräften (13,57 m/s) in einem Laborwindkanal. Ergänzend wurden Feldversuche über einem Zeitraum von 28 Tagen in einem nordrhein-westfälischen Braunkohletagebau durchgeführt. Dabei wurden Bodenbeete angelegt und in regelmäßigen Abständen mit einem Laubgebläse winderodierenden Kräften (14,65 m/s) ausgesetzt. Die Konzentrationen der suspendierten Bodenpartikel (TSP, PM_{10}, $PM_{2,5}$) wurden mit einem Laser-Photometer (DustTrak DRX 8533) erfasst. Die Ergebnisse bestätigten die Wirksamkeit von ANL zur Verbesserung der Winderosionsbeständigkeit von Grubenböden unter Umweltbedingungen, zeigten jedoch eine Anfälligkeit gegenüber abiotischen und biotischen Einflüssen, insbesondere durch Wasser. Die Auslaugungsversuche legten dar, dass wiederholende Nass-Trocken-Zyklen zu einem erhöhten Bodenverlust führten, während entgegen den Erwartungen eine höhere Niederschlagsintensität mit einem geringeren Bodenverlust einherging. Die Feldversuche zeigten, dass die Anwendung von ANL im Vergleich zu unbehandelten und mit Wasser behandelten Böden signifikant niedrigere Maximalkonzentrationen von suspendierten Feinstaub bewirkte. Böden, die mit ANL behandelt wurden, wiesen PM_{10}-Konzentrationen zwischen 1,7 und 5,0 mg/m³ ($PM_{2,5}$: 0,9–3,2 mg/m³; TSP: 2,7–8,5 mg/m³) auf, während unbehandelte bzw. mit Wasser behandelte Böden deutlich höhere PM_{10}-Werte von 59,0 mg/m³ ($PM_{2,5}$: 31,1 mg/m³; TSP: 77,1 mg/m³) bzw. 27,7 mg/m³ ($PM_{2,5}$: 21,0 mg/m³; TSP: 39,2 mg/m³) erreichten. Bei einer weiteren Auswertung der Daten wurde ein sukzessiver Anstieg der Partikelemissionen über die Zeit festgestellt, der primär auf anhaltende Niederschläge zurückzuführen ist.

Zusammenfassend belegen die Forschungsergebnisse, dass ANL die Winderosionsbeständigkeit von Böden durch Partikelagglomeration wirksam erhöhen können. Daraus lässt sich schließen, dass ANL das Potential haben, als Staubbindemittel zur Reduzierung von Staubemissionen, welche infolge von Winderosion auf exponierten Grubenböden entstehen, eingesetzt zu werden. Die gewonnenen Erkenntnisse erweitern das bestehende Wissen darüber, wie kohlenhydrat- und proteinbasierte Stoffe als Staubbindemittel angewendet werden können, was den Weg für die Entwicklung von kosteneffizienteren und umweltfreundlicheren Strategien zur Staubbekämpfung im Bergbau und in weiteren Industriezweigen ebnen kann. Darüber hinaus können die Ergebnisse lebensmittelverarbeitenden Betrieben dabei helfen, neue Einnahmequellen zu erschließen und ihre Abfallmengen zu minimieren, was zu einer stärker kreislauforientierten Wirtschaft beiträgt.

English Abstract

Mine and mineral processing sites are significant sources of mineral dust emissions, with wind erosion of exposed mine soils as a primary contributor. Applying dust suppressants is a proven mitigation strategy, but conventional options (e.g., watering and synthetic polymers) along with emerging bio-based alternatives (e.g., biopolymers) face notable limitations. These include high product prices, substantial water consumption, significant carbon footprints, potential damage to ecosystems and operational challenges in application.

The utilization of food processing wastes and by-products (FPWB) represents a feasible solution for environmentally friendly dust suppression, offering both cost-effectiveness and ease of application. These materials are biodegradable, readily dissolvable in cold water without affecting viscosity, inexpensive to acquire and composed of carbohydrates and proteins, which have been shown to enhance resistance to wind erosion. Despite their promising potential as dust suppressants, FPWB have received surprisingly little research attention. This dissertation aims to bridge this gap by investigating their potential to control wind-blown dust emissions from exposed mine soils. The research work is structured in three studies, the results of which have been published in three articles.

The first study (p. 41 ff.) analyzed the unconfined compressive strength (UCS) to assess the ability of FPWB to agglomerate soil particles, a key dust suppression mechanism. Sixteen FPWB were tested at concentrations of 2 wt% and 4 wt% on medium-to-coarse-grained sand, the same substrate used in the experiments conducted in phases 2 and 3. The results showed that incorporating FPWB into the soil significantly increased its mechanical strength. While untreated soil exhibited a UCS of 11 kPa, the most effective materials achieved strengths ranging from 1,366 to 2,026 kPa, with one material reaching 7,535 kPa. These values are comparable to, and in some cases exceed, those reported in the literature for commercial biopolymers. Further analysis indicated that FPWB rich in proteins and polysaccharides generally produced greater soil strength improvements than those dominated by low molecular weight carbohydrates.

As UCS test data can only provide indirect evidence of the effectiveness of reagents in reducing wind erosion, the second study (p. 63 ff.) evaluated the ability of FPWB to modify soil surfaces to withstand erosive forces. Four FPWB were examined at varying concentrations (1–10 %) and application rates (0.25–3 L/m²) using laboratory wind tunnel tests at 13.57 m/s. The results demonstrated that FPWB applications substantially reduced wind-induced soil loss, with all materials achieving reductions of over 99 %, vastly outperforming conventional watering which reduced soil loss by 39 %. The data further revealed that each material had an optimum concentration and application rate, ranging between 5–10 % and 0.75–1.5 L/m², respectively. Exceeding these thresholds resulted in negligible or minimal improvements in effectiveness.

The third study (p. 79 ff.) investigated the effects of environmental exposure on the effectiveness of FPWB in establishing wind erosion-resistant soil surfaces, as abiotic and biotic factors significantly influence the durability of dust suppressants. Initially, leaching tests were conducted with four FPWB which were exposed to a series of wetting-drying cycles combined with varying intensities of rainfall (0.25–4 L/m²). Samples were then subjected to laminar airflow of 13.57 m/s within a laboratory wind tunnel. Subsequently, field trials were carried out over 28 days at an open-pit lignite mine in North Rhine-Westphalia, Germany. Soil plots were established and periodically exposed to wind erosion (14.65 m/s) using a commercial electric blower, and suspended particulate concentrations (TSP, PM_{10}, $PM_{2.5}$) were recorded with a laser photometer-based aerosol monitor (DustTrak DRX 8533). The results not only confirmed the ability of FPWB to enhance wind erosion resistance under environmental exposure, but also revealed vulnerability to abiotic and biotic factors, particularly water. Leaching test data showed that repetitive wetting-drying cycles led to increased soil loss, while contrary to expectations, higher rainfall intensity reduced it. Field trials demonstrated that FPWB treatments significantly lowered peak particulate concentrations compared with untreated or water-treated soils. Soils reinforced with FPWB exhibited PM_{10} concentrations ranging from 1.7 to 5.0 mg/m³ ($PM_{2.5}$: 0.9–3.2 mg/m³; TSP: 2.7–8.5 mg/m³), whereas untreated soil and water-treated soil showed PM_{10} levels of 59.0 mg/m³ ($PM_{2.5}$: 31.1 mg/m³; TSP: 77.1 mg/m³) and 27.7 mg/m³ ($PM_{2.5}$: 21.0 mg/m³; TSP: 39.2 mg/m³), respectively. Further data analysis showed a gradual increase in particulate emissions over time, predominantly attributed to prolonged rainfall.

In conclusion, this research demonstrates that FPWB can increase the wind erosion resistance of soils through particle agglomeration. This provides empirical support that FPWB have the potential to be used as dust suppressants to reduce dust emissions caused by wind erosion on exposed mine soils. These findings have implications for deepening our understanding of how carbohydrate- and protein-based substances can act as dust suppressants, how environmental factors can impact their effectiveness over time, and at what application rates and concentrations they are effective. This knowledge can pave the way for developing more cost-effective and environmentally-friendly dust control strategies in mining and other industries. Furthermore, the findings can help food processing companies create new revenue streams and minimize their amount of waste, contributing to a more circular economy.

PhD-Related and Other Publications

Below is a list of works published by the author during his doctoral studies. Some of these works are cited in the text and therefore also appear in the full bibliography.

Peer-reviewed articles

- **Freer, J.**; Bucher, P. G.; Braun, M.; Lottermoser, B. G. (2022): Food processing by-products and wastes as potential dust suppressants at mine sites. Results from unconfined compressive strength testing. In J. Air Waste Manag. 72 (9), pp. 1012–1026. DOI: 10.1080/10962247.2022.2072975.
- **Freer, J.**; Lübeck, M.; Sieger, J. L.; Lottermoser, B. G.; Braun, M. (2022): 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), p. 11551. DOI: 10.3390/app122211551.
- Sieger, J. L.; Lottermoser, B. G.; **Freer, J.** (2023): Evaluation of protein and polysaccharide biopolymers as dust suppressants on mine soils. Laboratory experiments. In Appl. Sci. 13 (2). DOI: 10.3390/app13021010.
- Sieger, J. L.; Lottermoser, B. G.; **Freer, J.** (2023): Effectiveness of protein and polysaccharide biopolymers as dust suppressants on mine soils. Results from wind tunnel and penetrometer testing. In Appl. Sci. 13 (7), p. 4158. DOI: 10.3390/app13074158.
- Sieger, J. L.; Lottermoser, B. G.; **Freer, J.** (2023): Effectiveness of protein and polysaccharide biopolymers as dust suppressants on mine soils. Large-scale field trials. In Mining 3 (3), pp. 428–462. DOI: 10.3390/mining3030026.

Preprints

- **Freer, J.**; Sieger, J. L.; Lottermoser, B. G.; Braun, M. (2022): Effectiveness of food processing by-products in suppressing wind-induced dust emissions from mine soils. Results from laboratory wind tunnel experiments. Available online at https://ssrn.com/abstract=4220674.

Conference contributions

- **Freer, J.**; Hennig, A.; Vossen, P.; Lehnen, F. (2018): Installation and performance of passive dust samplers on tailing ponds. In Lottermoser, B. G. (Ed.): Abstract Volume. 1. International Conference Mines of the Future. 1. International Conference Mines of the Future. Aachen, May 23 - 24, 2018: RWTH Aachen University, p. 70.
- **Freer, J.**; Futschek, F.; Sieger, J. L. (2020): Aqueous surfactant solutions for dust suppression in open pit mines. The influence of different soil textures on wettability. In Lottermoser, B. G. (Ed.): Abstract Volume. First International Confer-

ence Mineral Resources for Future Generations: AIMS 2020. 1. International Conference Mineral Resources for Future Generations. Aachen, March 2 - 3, 2020: RWTH Aachen University, p. 46.

- Sander, J. N.; Küpper, N. M.; **Freer, J.**; Lottermoser, B. G. (2022): The use of satellite remote sensing and machine learning algorithms for identification, measurement and classification of mine waste sites. In EARSeL (Ed.): Proceedings of the 12th EARSeL Workshop on Imaging Spectroscopy. 12th EARSeL Workshop on Imaging Spectroscopy. Potsdam, June 22 - 24, 2022.
- Sander, J. N.; Küpper, N. M.; Richter, L.; **Freer, J.**; Lottermoser, B. G. (2022): Satellite remote sensing data and artificial intelligence systems to identify, measure and class mine waste piles. In European Space Agency (Ed.): Proceedings of the Living Planet Symposium 2022. Living Planet Symposium 2022. Bonn, May 23 - 27, 2022.
- Sieger, J. L.; Lottermoser, B. G.; **Freer, J.** (2023): Field trials evaluating the potential of biopolymers as dust suppressants on mine soils. In Lottermoser, B. G. (Ed.): Proceedings of the 1st European Conference on TEaching and Research in Sustainable Resource ExtrAction. 1. European Conference on TEaching and Research in Sustainable Resource ExtrAction. Boppard, September 6 - 8, 2023: RWTH Aachen University, p. 50.

CRediT Author Statement

The thesis contribution statement is based on the contributor roles taxonomy (CRediT).

Author

- *Justus Freer* is the main author of this thesis and its three associated research articles and took the lead in most aspects of the work. His responsibilities included Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization, and Project Administration. He also contributed equally to Writing – Review and Editing across all publications.

Co-Authors

- *Bernd Georg Lottermoser* is the doctorate supervisor and co-authored all three research articles, where he contributed equally to Writing – Review and Editing.
- *Marius Braun* co-authored all three research articles, providing supporting contributions in Conceptualization. For the first research article, he also offered supporting input on Methodology.
- *Johannes Lukas Sieger* co-authored the second and third research articles. His contributions included supporting roles in Conceptualization, Methodology, and Writing – Review and Editing for both publications.
- *Wolf Peter Gregor Bucher* co-authored the first research article, where he contributed equally to Investigation and provided supporting work in Data Curation.
- *Maximilian Lübeck* co-authored the third research article, making an equal contribution to Investigation.

Other Contributors

- *Bernd Jürgen Müller* provided assistance with the design and construction of the wind tunnel in research articles 2 and 3.
- *Devrim Gürsel*, *Martin Knippertz*, and *Stephanie Lohmeier* assisted with the soil characterization, including mineralogy, particles size distribution, pH-value, specific gravity, and soil color.
- *RWE Power AG* supported this thesis by enabling field trials at the Inden open-pit lignite mine. Key contributors from RWE included *Klaus Gödde*, *Dennis-Marc Schier*, and *Eva Thelen*.
- *Rheinische Baustoffwerke GmbH* provided bulk samples of the mine soil tested in all thesis experiments.
- Numerous *anonymous reviewers* offered critical feedback during the peer review process of the research articles.

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List of Abbreviations

Abbreviation	Meaning
Al_2O_3	aluminum oxide
AM	apple molasses
ANL	Abfall- und Nebenprodukte der Lebensmittelverarbeitung
ANOVA	analysis of variance
B	by-product
BM	beet molasses
BV	beet vinasses
CM	chicory molasses
CV	chicory vinasses
d	day
D_{50}	particle size diameter (mm) at which 50 % of a soil samples volume have a finer particle-size
df	degrees of freedom
DG	dextrose greens
DM	dry matter
DS	decantation syrup
DWC	deproteinized whey concentrate
EICP	enzyme induced carbonate precipitates
EU	European Union
F	F-statistic
FC	filter concentrate
FPWB	food processing wastes and by-products
GSR	glucose syrup retentate
H_2O	water
HCl	hydrochloric acid
$HClO_4$	perchloric acid
HF	hydrofluoric acid
HNO_3	nitric acid
ICP-MS	inductively coupled plasma mass spectrometry

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Abbreviation	Meaning
K_2O	potassium oxide
M	mean
MAX	maximum
MDD	maximum dry density
MgO	magnesium oxide
MICP	microbial-induced carbonate precipitates
MIN	minimum
MnO	manganese(II) oxide
MPP	milk permeate powder
MS	mean square
Mt	million tons
n	sample size
N/A	not available
Na_2O	sodium oxide
OMC	optimum moisture content
p	p-value
P_2O_5	phosphorus pentoxide
PAM	palatinose molasses
PI-SWERL	portable in-situ wind erosion lab
PM	particulate matter
PM_{10}	mass fraction of particulate matter with an aerodynamic diameter of 10 micrometers or less
$PM_{2.5}$	mass fraction of particulate matter with an aerodynamic diameter of 2.5 micrometres or less
R-1	replicate 1
R-2	replicate 2
R-3	replicate 3
RWJP	rinsing water from jam production
SD	standard deviation
SiO_2	silicon dioxide
SM	poorly graded non-plastic silty sand
SP	poorly graded sand
SPEC	specification
SP–SM	poorly graded sand with silt
SS	sum of squares
SW-SM	well-graded sand with silt

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Abbreviation	Meaning
TiO_2	titanium dioxide
TM	total mass
TSP	total suspended particulate
TWL	total weight loss
UCS	unconfined compressive strength
US	untreated soil
UV	ultraviolet
VAL	value
W	waste
WDC-1	wet-dry cycle 1
WDC-2	wet-dry cycle 2
WDC-3	wet-dry cycle 3
WDC-4	wet-dry cycle 4
WPP	whey permeate powder
XRD	x-ray diffraction
α	significance level

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Chapter 1
General Introduction

1.1 Motivation

1.1.1 Context

The anticipated rise in mining activities in Europe raises concerns about potential environmental impacts. Numerous studies have documented that mine and mineral processing sites emit substantial amounts of mineral dust particles and associated contaminants into the atmosphere (Duarte et al. 2022; Csavina et al. 2012; Mishra and Das 2017; Hendryx et al. 2020; Mpanza et al. 2020; Momoh et al. 2013). For instance, a study by Hendryx et al. (2020) examined the implications of air pollutants from Australian coal mining on public and occupational health, revealing significant emissions of NOx, metals, and particulate matter. Noteworthy, particulate matter concentrations were significantly elevated in communities with mining than in non-mining communities. Mpanza et al. (2020) reported similar results, highlighting the health hazards posed to surrounding villages by particulate matter emissions and dust fallout emanating from abandoned, poorly rehabilitated tailings impoundments. A case study by Momoh et al. (2013) corroborates these findings, demonstrating that mine dust in ambient air poses significant risks to the health of mine workers and residents of communities surrounding mine sites. Exposure to dust can trigger a spectrum of diseases, including asthma, pulmonary fibrosis, gastric and lung cancer or pneumoconiosis (Moshammer and Neuberger 2004; Kang et al. 2021; Alnabwani et al. 2022; Gautam et al. 2016).

Beyond its health implications, mine dust poses substantial environmental and operational challenges. Numerous studies show that dust can contaminate soil and water systems, and harm flora and fauna (Pyatt 1973; Shukla et al. 1990; Thompson et al. 1984; Darley 1966; Flückiger et al. 1979). High levels of dust, in turn, can reduce visibility, constituting a critical safety concern in both workplaces and on haul roads. (Du Plessis et al. 2016; Olson and Veith 1987; Gautam et al. 2016; Rushing and Tingle 2007). Dust can also lead to premature wear and tear on engines and moving equipment parts, reducing overall productivity and incurring increased operating and maintenance expenses (Bolander and Yamada 1999; Olson and Veith 1987). Additionally, dust can be perceived as a nuisance by residents near mining operations, negatively impacting public perception of mining activities (Blight 2008; Mpanza et al. 2020).

The erosion of mine soil by wind constitutes a major contributor to the overall dust load generated at mine and mineral processing sites, as evidenced by various studies (Huertas et al. 2011; Ghose 2004; Ghose and Majee 2000; Chang et al. 2010). A study by Chang et al. (2010), for instance, established wind erosion of bare grounds as the second primary source of dust, accounting for 20-40 % of total suspended particulate emis-

sions at gravel processing sites. Huertas et al. (2011) reported similar results for coal mining and identified heavily trafficked unpaved haul roads, material handling and wind erosion as main sources of total suspended particulate emissions.

1.1.2 Problem Statement

Dust suppressants are widely used in the mining industry to control dust emissions from wind erosion of mine soils. Numerous types of dust suppressants are described in the literature (cf., Table 1-1), but many have limitations and shortcomings. For example, water provides only extremely limited effectiveness due to rapid evaporation. Bolander and Yamada (1999) report that water generally maintains adequate dust suppression from 0.5 to 12 hours. Consequently, watering requires frequent re-application intervals, escalating operating costs and wasting valuable water resources, which is especially critical in regions with water scarcity (Du Plessis et al. 2016; Thompson and Visser 2007).

Hygroscopic salts absorb moisture from the atmosphere and thus require specific ambient conditions to suppress dust effectively (Monlux and Mitchell 2007; Wu et al. 2007). For example, Han (1992) states that sodium chloride starts to absorb water at 76 % relative humidity (25 °C). That implies, in turn, that hygroscopic reagents are not expedient dust suppressants in arid and semi-arid areas (Melese et al. 2018; Foley et al. 1996). Other problems associated with the application of chloride salts are increased maintenance costs due to corrosion on equipment and negative impacts on soil, vegetation and aquatic life (Rushing and Newman 2010; Goodrich et al. 2009; Tiwari and Rachlin 2018).

Organic petroleum-based products, such as bitumen emulsions, are classified as long-lasting dust suppressants because they are not soluble in water and thus resist leaching (Thompson and Visser 2007; Dalton 2013). However, their application poses a risk to occupational health and is associated with high expenses (Noble et al. 2017; Edvardsson et al. 2012; Schlüter 2011). Moreover, such products contain several contaminants (e.g., naphthenic acids, polyaromatic hydrocarbons (PAHs), metals) detrimental to the environment (Robidoux et al. 2018; Dew et al. 2015). A panel of experts sponsored and organized by the U.S. Environmental Protection Agency concluded that potential environmental impacts are highest from organic petroleum products and thus should not be applied to non-traffic areas (Piechota et al. 2004).

Synthetic polymer emulsions provide excellent dust suppression effectiveness. Unlike some other dust suppressant types, treatments with these products are considered more costly, and their formed crusts tend to embrittlement due to oxidative ageing, resulting in reduced effectiveness over time (Huertas et al. 2011; Noble et al. 2017; Yousif and Haddad 2013; Xu et al. 2018). In addition, synthesizing polymers from petroleum leads to growing levels of atmospheric carbon dioxide, contributing to climate change and global warming (Miller 2014).

Current research is focused on exploring biopolymers as a more environmentally friendly alternative to traditional dust suppressants. However, numerous biopolymers currently being investigated have characteristics that may restrict their use as dust suppressants. Firstly, some biopolymers, including gellan gum and chitosan, have solubility behaviors in water (e.g., requiring high temperatures or pH adjustments for dissolution) that can complicate their preparation and application as dust suppressants (Mudgil et al. 2014; Chang et al. 2016a; Hataf et al. 2018). Secondly, certain biopolymers, like guar

gum, can primarily be procured from regions outside Europe, which hampers developing regional sourcing strategies to reduce the carbon footprint and costs of dust control measures within the EU (Ding et al. 2020; Ding et al. 2021). Finally, several biopolymers, such as chitosan and pectin, have high product prices, rendering particularly temporary and short-term dust control efforts expensive (Lemboye et al. 2021; Kavazanjian et al. 2009; Chen et al. 2015).

Apart from biopolymers, enzyme-induced calcite precipitation (EICP) and microbiologically induced calcium carbonate precipitation (MICP) are increasingly being investigated as environmentally friendly techniques for dust suppression and wind erosion control (Almajed et al. 2020; Hamdan and Kavazanjian 2016; Dagliya et al. 2022; Chae et al. 2020; Sun et al. 2021a; Sun et al. 2021b). Both EICP and MICP are biomineralization techniques that agglomerate soil particles through the precipitation of calcium carbonate ($CaCO_3$). While EICP utilizes purified enzymes to induce the precipitation of $CaCO_3$, MICP harnesses the metabolic processes of bacteria. However, certain shortcomings hinder their application for dust suppression on a commercial scale. The main limitation of EICP's use is its high cost, while applying MICP is significantly challenging in the field (Hamdan and Kavazanjian 2016; Wang et al. 2017; Krajewska 2018; Saif et al. 2022; Chang et al. 2016b).

1.1.3 Research Gap

In summary, the current body of knowledge suggests a pressing need to identify environmentally friendly alternatives that can effectively suppress dust emissions while being cost-effective and easy to apply. One promising approach is the investigation of food processing wastes and by-products. Their application potential as dust suppressants can be deduced from a number of inherent properties. Firstly, wastes and by-products from food processing are commonly unavoidable, abundant within Europe and typically inexpensive to acquire, rendering them attractive options for cost-effective dust suppression applications (Anal 2017; Mahro et al. 2015; Torres-León et al. 2018; Teigiserova et al. 2019; Osorio et al. 2021; Jayathilakan et al. 2012).

Moreover, some food processing wastes and by-products are rich in carbohydrates and proteins, which hold promise in application as eco-sensitive dust suppressants due to their techno-functional properties (Jõgi and Bhat 2020; Sharma et al. 2020; Torres-León et al. 2018). Carbohydrates are molecules composed of carbon, hydrogen and oxygen atoms and can be categorized into monosaccharides, disaccharides, oligosaccharides and polysaccharides (Wrolstad 2012). Proteins, in turn, are macromolecules consisting of amino acid residues linked by peptide bonds (Zayas 1997). Such biomolecules can be broken down by microorganisms like bacteria, fungi and yeasts. This natural degradation process results in environmentally friendly products such as water, carbon dioxide and biomass. Biodegradable materials are expected to have minimal adverse environmental impacts when employed as dust suppressants (Piechota et al. 2004; He and Benson 2013; Jiang and Zhang 2013; Rudnik 2013). Furthermore, certain carbohydrate and protein fractions exhibit excellent solubility in cold water, making them easy to prepare and apply as dust suppressants (Anal 2017; Ribeiro et al. 2022).

The most important feature of carbohydrate- and protein-rich food processing wastes and by-products is their potential to suppress wind-blown dust emissions. Numerous studies demonstrated that carbohydrates and proteins can strengthen soil, indicating the ability to agglomerate soil particles, which is one mechanism by which dust

suppressants act (Soldo et al. 2020; Chang et al. 2018; Chen et al. 2016; Choi et al. 2020; Fatehi et al. 2018; Soldo et al. 2022; Xu et al. 2018). For example, Fatehi et al. (2018) reported that sand treated with casein and sodium caseinate, both proteins from the dairy industry, had significantly higher mechanical strength than untreated soil. Unconfined compression tests by Soldo et al. (2022) confirmed that polysaccharides, namely xanthan gum and guar gum, can effectively strengthen silty sand.

Moreover, laboratory-based wind tunnel studies acknowledged the effectiveness of carbohydrates and proteins in establishing erosion-resistant soil surfaces (Chen et al. 2015; Lemboye et al. 2021; Nouri et al. 2022; Ayeldeen et al. 2017; Toufigh and Ghassemi 2020; Owji et al. 2021; Omane et al. 2017; Kavazanjian et al. 2009). For instance, Owji et al. (2021) investigated the potential of two polysaccharides for soil erosion control. Their wind tunnel experiments revealed a remarkable reduction in soil loss, with carboxymethyl cellulose and guar gum solutions achieving > 99% and > 97% reductions, respectively, compared to untreated samples (Owji et al. 2021). Similarly, Omane et al. (2017) reported an > 99% effectiveness for sugar beet molasses, a by-product of sugar production rich in mono- and disaccharides, in mitigating soil loss. Sugar beet molasses is also mentioned in numerous best practice guides as an effective dust suppressant (Dalton 2013; Piechota et al. 2004; Bolander and Yamada 1999; Jones 2017). Furthermore, field trials conducted by Parsakhoo et al. (2020) over an 81-day period confirmed the effectiveness of sugar beet molasses in controlling dust emissions from unpaved forest roads.

Despite the promising potential as dust suppressants, food processing wastes and by-products have received surprisingly little research attention. To date, only a handful of studies have investigated their effectiveness in suppressing dust emissions, including those conducted by Gotosa et al. (2015), Parsakhoo et al. (2020), Omane et al. (2017) and Liu et al. (2022). This lack of research highlights the need for further investigation to fully understand the limitations and potential of food processing wastes and by-products as environmentally friendly dust suppressants.

1.2 Theoretical Framework

This section defines and explains the key concepts, theories, and terminology used in this research to ensure clarity and prevent ambiguity or misinterpretation.

1.2.1 Dust Suppressants

In academic discourse, there is neither a standard definition nor a generally accepted classification of dust suppressants. Piechota et al. (2004), for example, classify dust suppressants based on their composition, a modified version from Bolander and Yamada (1999). Most materials used for dust suppression can probably be grouped into one of the eight categories shown in Table 1-1. Other classifications were issued by Jones (2017), Cecala et al. (2012), Thompson and Visser (2002), Dang and Shan (2018) and Parvej et al. (2021).

This thesis defines dust suppressants as materials that are applied to soil surfaces to restrict the release of dust particles into the atmosphere. In the broadest sense, the definition includes physical covers (e.g., vegetation), water and other reagents that are applied dry, as emulsions, suspensions, or solutions. However, the present work focuses solely on dust suppressants that are applied as liquids to mine soils. Common synonyms

used for dust suppressants are dust palliatives, dust control agents, dust control products, or dust control chemicals.

Table 1-1. Classification of dust suppressants according to Piechota et al. (2004).

Category	Examples
Water	Fresh and seawater
Salts and brines	Calcium chloride, magnesium chloride
Petroleum-based organics	Asphalt emulsion, cutback solvents, dust oils, modified asphalt emulsions
Non-petroleum based organic	Vegetable oil, molasses, animal fats, lignosulfonate, tall oil emulsions
Synthetic polymers	Polyvinyl acetate, vinyl acrylic
Electrochemical products	Enzymes, sulfonated oils
Clay additives	Bentonite, montmorillonite
Mulch and fiber mixtures	Paper mulch with gypsum binder, wood fiber mulch mixed with brome seed

Dust suppressants work either by agglomeration, hygroscopicity, or a combination of both mechanisms. Products (e.g., synthetic polymers) that act by agglomeration cause a consolidated accumulation of previously loose soil particles as they set. In contrast, hygroscopic chemicals (e.g., calcium chloride) increase the soil moisture content by absorbing water from ambient air, thereby contributing to soil cohesion. In both cases, inter-particle bonding increments and thus the soil's resistance to erosive forces (Parvej et al. 2021; Huertas et al. 2011).

There are two basic methods for the application of dust suppressants to mine soils. They can be applied either by spraying them directly onto the surface or by incorporating them into the first substrate layer (Edvardsson 2009). Both techniques are used for initial applications and subsequent maintenance activities (Thompson and Visser 2007). Bare soils, which are mainly exposed to wind erosion, are generally treated topically. In contrast, the incorporation of dust suppressants into the ground is typical for trafficked areas such as unpaved roads (Piechota et al. 2004). Travel surfaces are repeatedly graded, moistened, compacted and sprayed with the dust suppressant solution (Gillies et al. 1999). According to Jones (2017) and Rushing and Tingle (2007), mix-in applications are labor-intensive but extend the treatment's service life and thus the interval between required maintenance activities.

Dust suppressants are typical applied with application rates ranging from 1.4 to 4.5 L/m² at solution strengths of 0.05 to 0.12 kg/L (Piechota et al. 2004). Trafficked areas tend to receive higher doses than those only exposed to wind erosion. The solutions can be sprayed either in one heavy application or in several light applications (Jones 2017). The latter avoids puddling and runoff, and supports the penetration of the dust suppressant into the soil. In addition, treatments should not be made just before rain as there is a risk of it washing off (Monlux and Mitchell 2007).

Dust suppressants do not act permanently and must be reapplied at regular intervals (Edvardsson et al. 2010). Lignin sulfonate, for instance, can keep mine haul roads dust-free for up to 4 weeks, while commercial products typically advertise a lifespan of 6-12 months (Cecala et al. 2012; Piechota et al. 2004). However, these claims should be interpreted cautiously since the durability of dust suppressants depends on a number of

factors, including weather, traffic conditions, dosage rate, application method and soil type (Steevens et al. 2007; Naeimi and Chu 2017). In this context, the term "durability" refers to the length of time a treatment can maintain effective dust suppression without requiring excessive maintenance.

Various types of equipment are available on the market to apply dust suppressants. In general, off-road water carts are used in the mining industry, which are available as articulated and rigid-frame trucks. Solutions are spread onto the ground either through spray nozzles, valves, or bars mounted at the vehicle's rear (Cecala et al. 2012). As the effectiveness of any dust suppressant treatment requires uniform product application, water carts should be equipped with a spray control system (Si and Herrera 2007). Such devices automatically regulate the amount of solution applied to the surface regardless of speed and other truck variables and sustain a spray pattern with minimal width variation. Water carts can also be fitted with water cannons and hoses, allowing treatments of difficult-to-access areas or slopes (Cecala et al. 2012).

In some cases, hydroseeders are utilized for dust suppression applications (Edwards et al. 2010; Rushing et al. 2006). Such equipment consists of powerful agitators and pumping aggregates that are capable of handling even heavy and highly viscous slurries. Suspensions are sprayed with high-pressure hoses or cannons onto the surface (Cereno et al. 2011; Emeka et al. 2021). A trace dye (e.g., green) is typically added to hydroseeding slurries to assist operators apply the suspension more uniformly onto the topsoil. Similar measures are also adopted when spraying dust suppressants.

On broader areas, Sieger et al. (2023a) demonstrated the potential of field sprayers to be used as an equipment for dust suppressant application. Field sprayers are typically used in agriculture to spread pesticides or fertilizers onto cropland (Nuyttens et al. 2007; Batte and Ehsani 2006). Such machines consist of a tank with an integrated agitator and are equipped with a boom containing multiple single nozzles spraying the solution evenly across the entire working width (Sharda et al. 2013; Wei et al. 2023). Field sprayer boom widths typically span a range from 18.2 to 36.5 meters (Batte and Ehsani 2006). One drawback, however, is that field sprayers are dimensioned for low-volume flow rates. This means that in scenarios where the installed pump capacity is insufficient to deliver the required application rate, it is necessary to either reduce the travel speed of the machine or apply the solution in several light applications. Accordingly, the application of dust suppressants with field sprayers is likely to be efficient only at low application rates.

1.2.2 Food Processing Wastes and By-Products

Food processing is a part of the food industry and refers to the transformation of agricultural products into food, or of existing foodstuff into alternative forms (Heldman and Hartel 1997; Brennan and Grandison 2012). It can be divided into primary, secondary, and tertiary processing (Grumezescu and Holban 2018). Primary processing involves techniques for the initial conversion of agricultural products into food, such cleaning, sorting, dehulling and milling. The products are either distributed to the retail market or sent to factories as ingredients for secondary or tertiary processing. Secondary processing involves processes that convert food ingredients into edible foods, such as baking bread or brewing beer. Tertiary processing converts foods into other value-added food products such as frozen meals or airline meals. These foods are typically ready-to-

eat or heat-and-serve and may contain a variety of additives and preservatives (Grumezescu and Holban 2018; Hitzmann 2017).

In the literature used, there is no standardized definition of food processing wastes and by-products. This thesis adopts the definitional framework from the EU Waste Framework Directive (European Union 2008). Based on Articles 3 and 5 of this Directive, food processing waste can be classified as any biogenic material arising from a food processing production process that the holder intends or is required to dispose of. Food processing by-products, on the other hand, can be defined as biogenic materials resulting from a food processing production process where the primary objective is not the generation of that material. Additionally, food processing by-products must adhere to the following criteria: (1) further use of the substance or object is certain, (2) the substance can be used directly without any further processing other than normal industrial practice, (3) the substance is produced as an integral part of a production process, (4) and further use is lawful (European Union 2008).

Food processing is inherently linked to the generation of substantial amounts of unavoidable wastes and by-products (Russ and Meyer-Pittroff 2004; van Ginkel et al. 2005; Narasimmalu and Ramasamy 2020; Kosseva 2009). A comprehensive study by Caldeira et al. (2019) estimated that in 2011, the EU's food processing industry produced 98.3 million tons (Mt) of by-products and 30.6 Mt of waste. However, statistics on food processing wastes and by-products must be viewed critically, as there are no standardized definitions. The abundance of these materials, coupled with their low market value and the fact that they are virtually unavoidable, render them ideal for secondary uses, such as dust suppression.

Table 1-2. Overview of generated food processing wastes and by-products (Mateos-Aparicio and Matias 2019).

Industry	By-products or wastes generated
Fruit and vegetable	Peelings, stems, seeds, shells, bran, trimmings, wastewater
Cereal and grain processing	Husks, hull, bran
Oil crop and pulse processing	Residues after extraction of oil from oilseed crops
Brewery and winery	Spent grain, hot trub, residual yeast, vine pruning, grape stalks, grape pomace, grape seeds, yeast lees, tartrate
Root and tuber processing	Starch, juice, sugar molasses, wastewater
Fish	Viscera, heads, offal, backbones, blood, shells
Meat	Carcasses, hides, hoofs, heads, feathers, manure, offal, viscera, bones, fat, meat trimmings, blood
Dairy	Whey, curd, milk sludge

The food processing industry produces various types of wastes and by-products (Wang et al. 2005; Kosseva 2009; Bharat Helkar and Sahoo 2016). These materials originate from plant or animal sources, with plant-derived materials contributing a considerably larger proportion compared to animal-derived ones. This disparity is likely to widen as the global trend shifts towards plant-based diets, as highlighted by Priefer et al. (2016). According to Mateos-Aparicio and Matias (2019), food processing wastes and by-products can be broadly categorized into eight groups based on their industry, shown in Table 1-2: (1) fruit and vegetable industry, (2) cereal and grain processing in-

dustry, (3) oil crop processing, (4) brewery and winery industry, (5) root and tuber processing, (6) marine industry, (7) meat industry, and (8) dairy industry.

The composition of food processing wastes and by-products depends on the type of raw material being processed, the type of product being produced and the production technology used (Mateos-Aparicio and Matias 2019). In general, these materials comprise different organic and inorganic components, including antioxidants, carbohydrates, fibers, flavor compounds, lipids, pigments, proteins and vitamins (Jõgi and Bhat 2020; Sharma et al. 2020; Torres-León et al. 2018).

1.2.3 Wind-blown Dust

The erosion of mine soil by wind is a major contributor to the total dust emitted from mining operations (Huertas et al. 2011; Ghose 2004; Ghose and Majee 2000). Mine soils, as defined in this thesis, are anthropogenic soils formed through mining activities and can consist of fragmented rock and native soils. Typical mine areas at risk of wind erosion are benches, berms, tailings dams and beaches, waste rock dumps, stockpiles, or unpaved roads.

Wind erosion refers to the physical process in which sediment is moved by wind. Shao (2008) distinguished the movement of particles into three distinct phases: (i) entrainment, (ii) transport and (iii) deposition. Initially, wind erosion detaches soil grains from the ground surface. It is initiated when the erosive forces exceed the soil's gravitational and cohesive forces (Chepil and Woodruff 1963; Shao and Lu 2000). Once detached, sediment particles are transported by the wind through one of three modes: creep, saltation or suspension (Blanco-Canqui and Lal 2008). Particle size dictates the mode of transport. Particles larger than 500 μm roll around the point of contact with the surface (creep). Particles ranging between 70 to 500 μm bounce along the surface (saltation). Particles less than 70 μm are lifted into the air (suspension) (Nickling and Neuman 2009). The final stage of wind erosion marks the deposition of transported particles onto a surface. Particles are deposited when the gravitational force is greater than the forces holding the particles in the air (Jarrah et al. 2020). For a comprehensive overview of the physics of wind erosion, see Shao (2008).

Li et al. (2024) state three mechanisms by which wind-induced dust is generated: (i) aerodynamic entrainment, (ii) disaggregation and (iii) saltation bombardment. Aerodynamic entrainment involves the lifting of dust particles into the air by aerodynamic drag and lift forces. Disaggregation refers to the ejection of dust particles from soil aggregates that are undergoing saltation. Saltation bombardment, on the other hand, entails the dislodgement of dust particles from soil aggregates due to the impact of saltating sand grains (Shao 2008; Shao et al. 1993). Shao (2001), Loosmore and Hunt (2000), and Lu and Shao (1999) all concur that aggregate disaggregation and saltation bombardment are the dominant dust-emission mechanisms.

A variety of factors influence the generation of dust by wind erosion, which interact with each other in complex ways. For example, higher wind velocities exert greater force on soil particles, facilitating their detachment and transportation (McKenna Neuman et al. 2009). Conversely, moist soil particles are more cohesive, raising the threshold friction velocity at which particles detach from the soil surface and become susceptible to wind-forced transport (Fécan et al. 1999; Chen et al. 1996). Soil properties, such as clay content, aggregation, physical and biological crusts, texture and organic matter, also sig-

nificantly impact the potential for dust generation by wind erosion (Lu and Shao 2001; Shao 2008).

Dust emitted from mine soils is mainly composed of mineral solids. Understanding its chemical and mineralogical composition is essential to assess the impact of dust exposure (Noble et al. 2017). The composition varies considerably depending on the specific minerals being extracted. Harmful dusts, for example, include those containing high levels of asbestos fibers (e.g., chrysotile), coal particles, crystalline silica (e.g., quartz), phyllosilicates (e.g., kaolinite) and various metals and metalloids (e.g., arsenic, cadmium and lead) (Plumlee and Ziegler 2003).

In addition to composition, particle size is a fundamental parameter to assess the potential hazards of dust to ecosystems and human health. There are numerous terms and definitions employed in air quality monitoring, environmental protection and occupational health and safety to categorize dust (Petavratzi et al. 2005). Presented below is a curated selection:

- *Total suspended particulate* (TSP) are all particles of solid and liquid droplets suspended in the air, with no specified size limit. However, they are typically less than 100 micrometers in diameter (Larssen and Hagen 1996).
- *Particulate matter* (PM) is the mass fraction of TSP that is small enough to be inhaled and causes serious health problems. PM is typically subdivided into PM_{10}, and $PM_{2.5}$ (Harrison et al. 2016; Li et al. 2015).
- *PM_{10}* is the mass fraction of PM with an aerodynamic diameter of 10 micrometers or less. The aerodynamic diameter represents the equivalent spherical diameter of a particle that would behave aerodynamically in the same manner as the actual particle in terms of its motion and deposition. PM_{10} can penetrate the upper respiratory tract, including the nose and throat (Harrison et al. 2016; Li et al. 2015).
- *$PM_{2.5}$* is the mass fraction of PM with an aerodynamic diameter of 2.5 micrometers or less. It can penetrate deep into the lungs, posing the greatest risk to human health out of all PM types (Harrison et al. 2016; Li et al. 2015).
- *Inhalable dust* is the mass fraction of TSP which is inhaled through the nose and mouth (Brown et al. 2013).
- *Thoracic dust* is the mass fraction of inhaled particles penetrating beyond the larynx (Brown et al. 2013).
- *Respirable dust* is the mass fraction of inhaled particles penetrating the unciliated airways (Brown et al. 2013).
- *Nuisance dust* is referred to as visible dust deposits on solid surfaces (Hunt 2011).

The specific health effects of mine dust exposure depend on various factors beyond composition and particle size, including shape, concentration, exposure frequency and duration, and bioaccessibility. For a comprehensive overview in this regard, see Plumlee and Ziegler (2003).

1.3 Thesis Aim, Central Research Question and Research Objectives

To address the research gap outlined in Section 1.1.3, this thesis aims to investigate the potential of food processing wastes and by-products as dust suppressants to

control wind-blown dust emissions from exposed mine soils. Accordingly, the present dissertation intends to answer the following central research question:

What is the potential for food processing wastes and by-products to be used as dust suppressants in the control of wind-blown dust emissions from exposed mine soils?

The thesis aim will be achieved through the following three research objectives:

I. Analyzing the ability to agglomerate soil particles.
II. Investigating the ability to modify soil surfaces to resist wind action.
III. Exploring the influence of environmental factors on the effectiveness of establishing wind erosion-resistant soil surfaces.

Research Objective I – The agglomeration of soil particles is one principal mechanism through which dust suppressants prevent the release of particulates into the atmosphere (Parvej et al. 2021). **Hence, the first step of this thesis is to analyze the ability of food processing wastes and by-products to agglomerate soil particles.** To achieve this objective, the unconfined compressive strength (UCS) test is employed, a widely recognized and applied method in dust suppressant research (Xu et al. 2018). The UCS test determines the maximum axial compressive stress that a cylindrical soil sample can withstand under unconfined conditions (DIN EN ISO 17892-7:2018-05). Here, an enhanced soil strength signifies increased resistance to erosive forces (Ding et al. 2021). This testing method is not only cost-effective, but also allows for a rapid assessment of soil strength, making it highly suitable for evaluating a vast number of food processing wastes and by-products as dust suppressants.

Research Objective II – While UCS test data provide useful insights, they can only offer indirect conclusions regarding the effectiveness of materials in preventing wind erosion (Xu et al. 2018). **To overcome this limitation, the subsequent step of this thesis is to investigate the ability of food processing wastes and by-products in modifying soil surfaces to resist wind action.** To accomplish this objective, laboratory-based wind erosion tests are conducted. In these experiments, treated mine soil samples are placed into a wind tunnel and subjected to simulated airflow. By measuring soil loss, this method allows us to directly quantify wind erosion resistance (Lemboye et al. 2021).

Research Objective III – The durability of dust suppressants is profoundly influenced by a combination of abiotic (e.g., temperature, radiation, water) and biotic (e.g., bacteria) factors (Gillies et al. 1999). Rainfall, in particular, can be a crucial factor in the effectiveness of water-soluble reagents because they can be leached from soil surfaces (Bolander and Yamada 1999; Toufigh and Ghassemi 2020). **Therefore, the final step of this research is to explore the influence of environmental factors on the effectiveness of food processing wastes and by-products in establishing wind erosion-resistant soil surfaces.** This objective is pursued by performing leaching tests in which treated mine soil samples are exposed to varying intensities of rainfall and repetitive wetting-drying cycles. A laboratory-based wind tunnel is used to expose the samples to controlled airflow. By measuring soil loss, the effect of rainfall on wind erosion resistance can be directly quantified. Subsequent field trials establish the effectiveness of food processing wastes and by-products over time under actual environmental conditions. Soil plots are eroded at regular intervals using a commercial electric blower and suspended dust con-

centrations are measured with a laser photometer-based aerosol monitor. This experimental setup introduces a novel approach, presenting an opportunity to evaluate a wide range of dust control products in a cost-effective and low-maintenance manner. Additionally, it is suitable for deployment in remote and hard-to-access areas.

1.4 Structural Outline

This PhD thesis is a compilation of three published works (i.e., two peer-reviewed journal articles and one pre-print) and is framed by a general introduction and a concluding discussion (Figure 1-1). Each publication (chapters 2-4) includes an introduction, materials and methods, a result, a discussion, and a conclusion section.

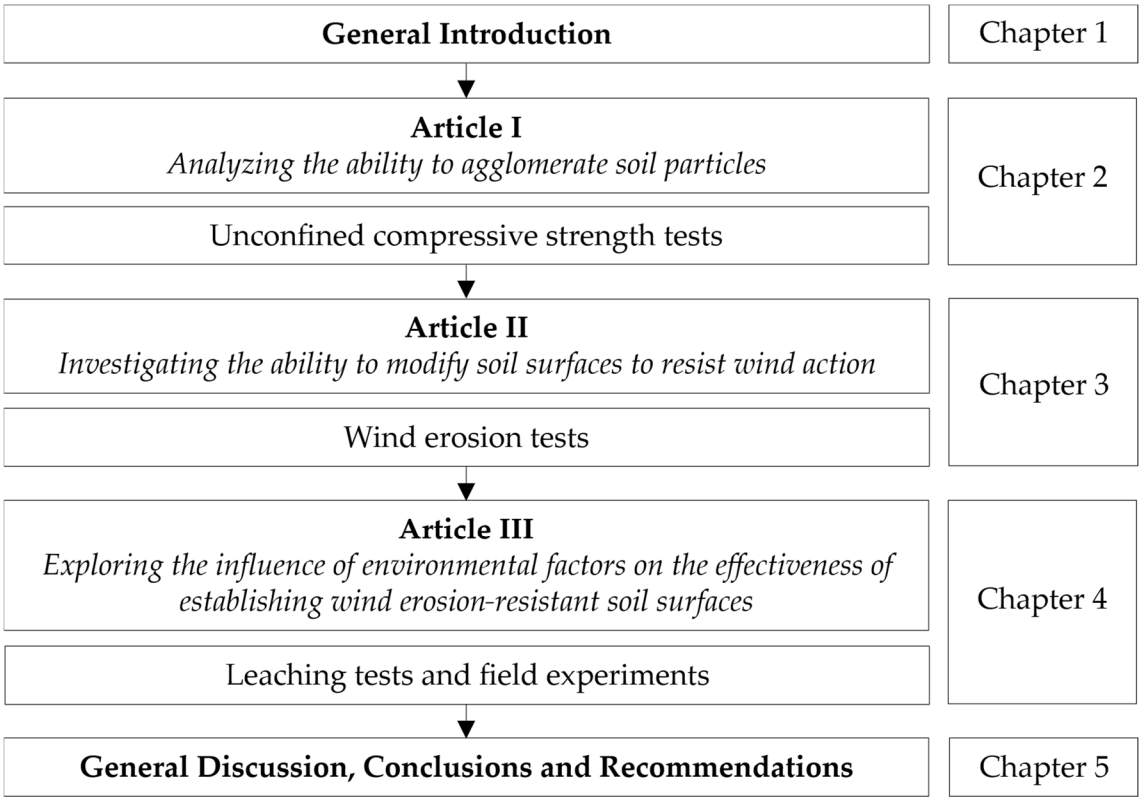


Figure 1-1. Dissertation structure and research approach.

Chapter 2 – Article I analyzes the potential of food processing wastes and by-products to agglomerate soil particles. A pre-selection is initially conducted to identify materials suitable for subsequent laboratory experimentation and exclude substances unsuitable for dust suppression at mine sites. UCS tests are then carried out to investigate the effect of selected materials on the mechanical strength of the test substrate. A detailed material characterization completes the study.

Chapter 3 – Article II investigates the wind erosion resistance of mine soil treated with food processing wastes and by-products. Wind erosion experiments are performed using a laboratory wind tunnel. Different additive concentrations and application rates are tested to establish the maximum wind erosion resistance.

Chapter 4 – Article III explores the influence of environmental factors on the effectiveness of food processing wastes and by-products as dust suppressants. Laboratory leaching experiments are conducted to study the impact of rainfall on wind erosion re-

sistance. Subsequent field tests establish the dust suppression effectiveness over time under actual environmental conditions.

Chapter 5 – The final chapter integrates the research findings into academic discourse and the broader context of dust suppressant applications. It begins by answering the central research question, followed by a SWOT analysis that evaluates the competitive position of food processing wastes and by-products within the dust suppressant market. The chapter concludes with a discussion of the implications of the research and recommendations for future work.

1.5 Significance

As climate change intensifies, with droughts and heatwaves becoming more frequent and severe, wind erosion poses a growing global threat (Overpeck and Udall 2020). In this context, research endeavors, such as this PhD thesis, that explore mitigation techniques for wind erosion hold immense significance.

The relevance of this work is further underscored by the substantial contribution of wind-blown dust to the overall dust load generated at mining and mineral processing sites (Huertas et al. 2011; Ghose 2004; Chang et al. 2010). Mitigating the erosion of mine soils by wind is therefore crucial for mining operations to minimize their environmental footprint, safeguard the health and safety of workers, and maintain the acceptance of stakeholders, including regulatory bodies, employees and local communities.

The research also is significant due to the limited knowledge available on the effectiveness of food processing wastes and by-products for dust suppression. Many of the materials studied have never been evaluated as dust suppressants before. Hence, this thesis extends our understanding on how food processing wastes and by-products can act as dust suppressants and provide precious information for future research.

The significance of the research is further highlighted by the lack of field data on the effectiveness of dust suppressants on barren surfaces subjected to wind erosion, as Katra (2019) noted. Additionally, Chang et al. (2020) emphasized the need for more research evaluating the durability and reliability of biomaterials, such as biopolymers, in geotechnical applications (e.g., dust suppression and wind erosion control) under real-world conditions.

The current trend in the food industry is towards zero-waste processes (Ribeiro et al. 2022). Research attempts, such as repurposing food processing wastes and by-products for dust suppression, can help the food industry close the loop and move towards a more circular economy.

Chapter 2
Ability to Agglomerate Soil Particles

A version of this chapter has been published in the Journal of the Air & Waste Management Association entitled "Food processing by-products and wastes as potential dust suppressants at mine sites: results from unconfined compressive strength testing".

Published	17 July 2022
Authors	Justus Freer, W. Peter G. Bucher, Marius Braun, and Bernd G. Lottermoser
Citation	Freer, J.; Bucher, P. G.; Braun, M.; Lottermoser, B. G. (2022): Food processing by-products and wastes as potential dust suppressants at mine sites. Results from unconfined compressive strength testing. In J. Air Waste Manag. 72 (9), pp. 1012–1026. DOI: 10.1080/10962247.2022.2072975.

2.1 Introduction

At mine and mineral processing sites, fugitive dust emissions from open pit faces, ore stockpiles, waste rock dumps, crushers, conveyor belts, concentrate sheds, tailings surfaces, and unpaved roads may contribute significantly to the natural particulate loading in the local atmosphere. Such additional particle emissions can make mining and mineral processing operations major sources of local air pollution. Significant dust emission may (a) become a nuisance; (b) reduce visibility and cause a hazard to mine personnel and especially equipment operators and drivers; (c) increase the wear and tear on moving parts of mining and processing equipment; (d) pollute nearby surface waters and topsoils; (e) lead to stunted vegetation growth by shading and clogging the pores of plants; and (f) impact on human health (Toufigh and Ghassemi 2020; Rai 2016; Thompson and Visser 2007, 2006). In particular, exposure of humans to particulate matter (PM) less than 10 and 2.5 μm (PM_{10} and $PM_{2.5}$, respectively) can lead to respiratory and cardiovascular ailments, whereas coarse particles (> PM_{10}) may reduce visibility on haul roads (Khan and Strand 2018; Rushing and Tingle 2007).

The amount of dust emitted from rock and soil surfaces correlates with the erodibility of the exposed material (i.e., the resistance of rocks and soils to erosion) and the erosive forces to which the substrate is subjected (Foley et al. 1996). A reduction in the erodibility of a substrate can be achieved by applying dust suppressants that establish linkages between single substrate particles and thus increase the resistance of the substrate to wind and traffic erosion (Thompson and Visser 2007). Therefore, dust suppression at mine sites commonly involves the use of water trucks to distribute water, or a mixture of water and additives to hold moisture and particles in dust emitting materials and to decrease dust emissions (Thompson and Visser 2002; Piechota et al. 2004).

A diversity of dust suppressants are commercially available, yet the applied chemicals are costly, and, in some cases, these additives are not necessarily readily available, easily applied, efficient and effective. Furthermore, the application of some of these chemicals may harm the environment, whereby water runoff from treated surface areas may impact on soils as well as surface and groundwater quality and cause toxicity to flora and fauna (Piechota et al. 2004). Hence, there is a clear need to identify readily available, non-toxic chemicals that are easily applied and help to suppress dust emissions efficiently and effectively at mine and mineral processing sites.

In this context, wastes and by-products from food production and processing may be sustainable alternatives to existing dust suppression chemicals, as some of them are known to agglomerate dust particles (Jones and Surdahl 2014; Omane et al. 2017; Jones 2017). Moreover, many of these materials are biodegradable and readily available and consist of low-molecular carbohydrates, polysaccharides and proteins that have adhesive characteristics (Anal 2017). The dust control effectiveness of polysaccharides and proteins has already been investigated by various studies, which concluded that these materials have a distinct potential to be applied in the mining sector (Chen et al. 2015; Reddy et al. 2020; Gillies et al. 1999; Ding et al. 2018). Both, polysaccharides and proteins, are biopolymers that can create three-dimensional networks structures by covalent or non-covalent bonds and have film-forming properties (Azeredo and Waldron 2016). Stickiness in food is often attributed to the presence of mono- and disaccharides (Adhikari et al. 2001). In fact, Omane et al. (2017) were able to demonstrate a dust control performance of > 99 % for beet molasses, which is a by-product from the refining of sugar

and primarily consists of sucrose. Therefore, it is possible that biopolymer- and sugar-rich wastes and by-products from food production and processing have the potential to bind single soil particles and reduce dust emissions.

The purpose of this study was to explore whether the use of biogenic wastes and by-products from the food production and processing influences the release of dust particles from mine soils. Material characterization and unconfined compressive strength tests (UCS) were performed on sandy soils treated with aqueous solutions of different additive concentrations. The UCS test is a suitable screening method because the UCS assessment is time- and cost-effective and correlates with wind tunnel tests (Xu et al. 2018). A higher UCS value indicates an enhanced wind erosion resistance, and thus an improved dust control performance (Ding et al. 2018). Prior to treatment, standard Proctor compaction tests were carried out to investigate the optimum water content of each soil-additive matrix to achieve maximum compaction of samples. Thus, UCS and Proctor tests were completed to evaluate: (a) the erodibility behavior of treated and untreated soils during laboratory trials; and (b) the relative effectiveness of selected biomaterials in lowering dust emissions from soils. Hence, this research adds to our understanding of dust suppressant treatment of soils and contributes to evaluating biogenic food wastes and by-products as environmentally friendly dust suppressants.

2.2 Materials and Methods

2.2.1 Soil

The soil used in this study represents a 2,500 kg bulk sample acquired from a sand and gravel pit in North-Rhine Westphalia. This material was selected for laboratory experimentation, because: (a) mine soils and surface mine exposures of industrial mineral and opencast lignite mines in North-Rhine Westphalia (Germany) have similar grain size distributions, and (b) the sample material is readily available, enabling further studies to be carried out.

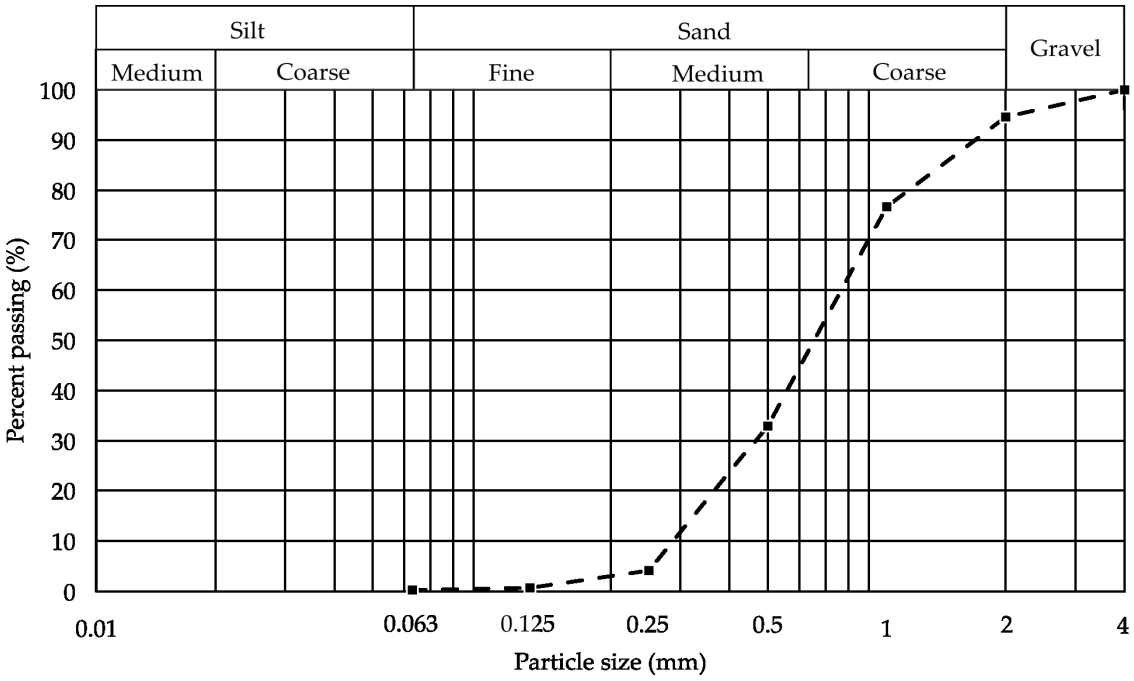


Figure 2-1. Particle size distribution of the soil sample (acc. to DIN EN ISO 17892-4:2017-04).

The investigated soil is medium-grained (medium-coarse sand; acc. to DIN EN ISO 14688-1:2018-05, and has a mean grain size (D_{50}) of 0.65 mm with a specific gravity of 2.56 g/cm³. The particle size distribution of the soil is illustrated in Figure 2-1. The sand has an optimum moisture content (OMC) of 9.7 % and a maximum dry density (MDD) of 1.741 g/cm³. Table 2-1 provides an overview of the physical and chemical properties of the soil sample, which were determined according to DIN, EN and ISO standards at RWTH Aachen University.

Table 2-1. Physical and chemical properties of the soil sample used for laboratory experimentation.

Parameter	Value	Unit	Test method
pH-value	6.4	-	DIN EN 15933:2012-11
Soil color	9.9YR 6.0/2.9	Munsell	Spectrophotometer Konica Minolta CM-5
MDD	1.741	g/cm³	DIN 18127:2012-09
OMC	9.7	%	DIN 18127:2012-09
Specific gravity	2.56	g/cm³	DIN EN ISO 11508:2018-04
Mean grain size (D_{50})	0.65	mm	DIN EN ISO 17892-4:2017-04

Table 2-2. Geochemical composition of soil sample.

Oxides	Content (wt%)
SiO_2	95.17
Al_2O_3	2.44
K_2O	1.19
Fe_2O_3	0.56
Na_2O	0.28
CaO	0.11
MgO	0.07
TiO_2	0.05
P_2O_5	0.03
MnO	0.01
Minor and trace elements	0.08

Note. The soil sample was analyzed using ICP-MS techniques and multi-acid (4-acid) digestion. The SiO_2 content was calculated by subtracting the sum of the contents of oxides and minor and trace elements from the total content.

Preparation of the sample for laboratory experimentation was conducted according to DIN 19747:2009-07. Soil sample homogenization and subsampling were carried out using a cement mixer and the coning and quartering technique. Representative subsamples were ground to powders using a vibratory disc mill, and an aliquot sample was subsequently analyzed by SGS Serbia using inductively coupled plasma mass spectrometry (ICP-MS) to determine the elementary composition of the soil. The combination of HCl (hydrochloric acid), HNO_3 (nitric acid), HF (hydrofluoric acid) and $HClO_4$ (perchloric acid) was applied for multi-acid (4-acid) digestion. The SiO_2 content was calculated by subtracting the sum of the contents of oxides and minor and trace elements from the total content. Geochemical analysis revealed major amounts of SiO_2 and minor concentrations of Al_2O_3, K_2O, Fe_2O_3, Na_2O, CaO, MgO, TiO_2, P_2O_5 and MnO (Table 2-2). The mineralogy of the soil was identified using X-ray diffraction (XRD) at the Clausthal Uni-

versity of Technology (Germany). The soil is dominated by quartz, with minor amounts of orthoclase, microcline and clinochlore.

2.2.2 Food Processing Wastes and By-Products

In the European Union (EU), approximately 16.9 Mt of food processing wastes and by-products are generated annually, with the German food industry contributing approximately 1.9 Mt (Stenmarck et al. 2016). In general, food production and processing generate a great diversity of wastes and by-products. Mahro et al. (2015) state that most of the wastes and by-products from German food production are used as animal feedstock. In this context, the Catalogue of Feed Material from the European Union (2017) provides a comprehensive overview of the material flows within the food industry. This document lists feed materials that are or may be intended for feeding (European Union 2017). In addition, a literature survey was conducted to identify suitable food processing residuals, and companies from the food industry were contacted directly regarding their wastes and by-products and relevant properties.

Subsequently, this study completed a selection process: (a) to identify food processing wastes and by-products suitable for subsequent laboratory experimentation; and (b) to exclude substances that are not suitable for dust suppression at mine sites. Such a selection procedure was based on a number of KO-criteria that, if not fulfilled, led to the inclusion, respectively exclusion of the substances from laboratory experimentation.

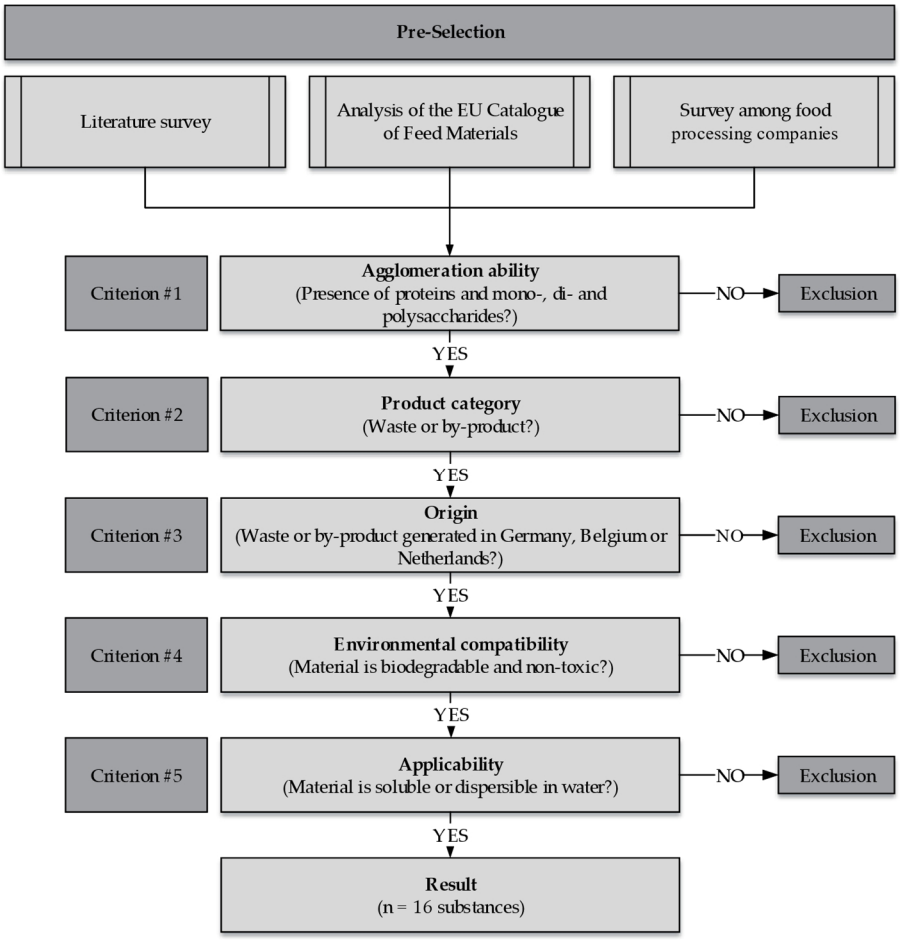


Figure 2-2. Flowchart showing the approach to pre-select wastes and by-products from the food processing industry for laboratory experimentation.

Figure 2-2 documents the approach and criteria to select wastes and by-products from the food processing industry for laboratory experimentation. The fundamental criterion for the use of a waste and by-product as dust suppressant is its ability to agglomerate dust particles (criterion 1). Such a material property is indicated by its stickiness and film-forming properties, respectively, the presence of proteins and mono-, di- and polysaccharides. Identified materials were then classified by this study into product, by-product or waste according to key provisions of Directive 2008/98/EC on waste from the Directorate-General for Environment (2012) (criterion 2). Following this, only wastes and by-products were selected, which are generated by German food producers, or by countries bordering the German state North-Rhine Westphalia (i.e., Belgium and Netherlands) (criterion 3). In addition, materials for further investigation had to have no adverse impact on the environment and be solely biodegradable and non-toxic (criterion 4). Also, the substance must be easy to apply at mine sites, and this criterion is fulfilled if the waste or the by-product is soluble or dispersible in water (criterion 5).

Table 2-3. Identified wastes and by-products from the food industry that have potential for applications as dust suppressants. The data was provided by the suppliers.

Substance	Origin	Product category	Supplier
AM	Obtained after producing pectin from apple pulp	B	agro Food Solution
BM	Obtained during the refining of sugar from sugar beets	B	Südzucker
BV	Derived from the industrial processing of musts/worts	B	Nordzucker
CM	Obtained during the production of inulin and oligofructose from chicory processing	B	BENEO-Orafti
CV	Obtained after the separation of inulin and oligofructose and ion exchange eluation from chicory processing	B	BENEO-Orafti
CDS	Obtained from the production of bioethanol from wheat and sugar beet	B	Südzucker
CSL	Concentrated liquid fraction from the steeping process of corn	B	Cargill Deutschland
DS	Syrup liquid obtained as a by-product of the candy sugar production	B	BENEO-Orafti
DWC	Partially deproteinized and delactosed whey concentrate obtained after ultrafiltration and crystallization of whey	B	MILEI
DG	Obtained after the production of dextrose from starch	B	Cargill Deutschland
FC	Filtration residues from milk protein production	W	Lactoland Trockenmilchwerk
GSR	By-product of wheat glucose production	B	Südzucker
MPP	Obtained by filtration of milk and from which lactose may have been partly removed	B	MILEI
PAM	Non-crystallized fraction from the manufacture of isomaltulose by enzymatic conversion of sucrose from sugar beets	B	BENEO-Orafti
RWJP	Cleaning of the production facility/removal of production residues (flushing batch)	W	Zentis
WPP	Obtained by filtration of whey and from which lactose may have been partly removed	B	MILEI

Note. Abbreviations: AM = Apple Molasses, B = By-Product, BM = Beet Molasses, BV = Beet Vinasses, CM = Chicory Molasses, CV = Chicory Vinasses, CDS = Concentrated Distillers Solubles, CSL = Corn Steep Liquor, DS = Decantation Syrup, DWC = Deproteinized Whey Concentrate, DG = Dextrose Greens, FC = Filter Concentrate, GSR = Glucose Syrup Retentate, MPP = Milk Permeate Powder, PAM = Palatinose Molasses, RWJP = Rinsing Water from Jam Production, W = Waste, WPP = Whey Permeate Powder.

The data required for criterion 4 and criterion 5 were provided by the identified suppliers. This study did not conduct any tests regarding the biodegradability, toxicity, or water solubility/dispersibility of the substances. By contrast, economic aspects (e.g.,

production volume, price) were not considered in the selection process because: (a) these factors depend on local conditions (e.g., production costs, transport distance, availability); and (b) there is insufficient economic data available. As a result, sixteen substances were identified that have potential to act as dust suppressants. Tables 2-3 and 2-4 provide an overview of the characteristics of the food processing wastes and by-products investigated by this study.

Table 2-4. Appearance, composition, and dry matter content of investigated food processing wastes and by-products.

Substance	Appearance	Composition	DM content (%)	
			SPEC [a]	VAL
AM	Viscous	Sucrose (63 % in DM); crude protein (3 % in DM); crude fiber (< 0.7 % in DM); short-chain oligosaccharides	69.0	69.5 [b]
BM	Viscous	Sucrose; glucose; fructose	75.0–85.0	79.2 [a]
BV	Liquid	Crude protein (33 % in DM); sucrose; glucose; fructose	55.0	53.9 [a]
CM	Liquid	Glucose, fructose, and sucrose (50–70 % in DM); crude protein (12 % in DM); chicory inulin and oligofructose.	72.0–76.0	72.8 [b]
CV	Viscous	Crude protein (45–51 % in TM)	60.0–70.0	63.3 [b]
CDS	Viscous	Crude protein (29.4 % in DM); crude fat (5.9 % in DM); crude fiber (3.5 % in DM); sucrose (9.2 % in DM); starch (3.5 % in DM)	26.3	N/A
CSL	Liquid	Crude protein (36–49 % in DM); starch, reducing sugars, crude fiber	25.0–35.0	27.0 [a]
DS	Viscous	Sucrose; glucose; fructose; oligosaccharides	65.0–75.0	72.0 [a]
DWC	Liquid	Lactose (25–35 % in DM); protein (2–5 % in DM); fat (max. 0.5 % in DM)	45.0–55.0	52.7 [a]
DG	Viscous	Dextrose (> 70 % in DM); disaccharides (> 9 % in DM)	58.0–65.0	61.2 [a]
FC	Solid	Protein	N/A	97.5 [b]
GSR	Viscous	Sucrose; glucose; fructose; protein; fat	> 25.0	25.9 [a]
MPP	Solid	Lactose (85 % in DM); protein (2.5 % in DM); fat (max. 1 % in DM)	≥ 97.0	99.4 [b]
PAM	Viscous	Isomaltulose and trehalulose (> 50 % in DM); sucrose, isomaltose, fructose and glucose (28–42 % in DM)	62.0–68.0	68.2 [b]
RWJP	Viscous	Sucrose; fruits; starch; pectin	N/A	33.2 [b]
WPP	Solid	Lactose (84 % in DM); protein (2.7 % in DM); fat (max. 1 % in DM)	≥ 97.0	99.0 [b]

Note. Abbreviations: AM = Apple Molasses, BM = Beet Molasses, BV = Beet Vinasses, CM = Chicory Molasses, CV = Chicory Vinasses, CDS = Concentrated Distillers Solubles, CSL = Corn Steep Liquor, DM = Dry Matter, DS = Decantation Syrup, DWC = Deproteinized Whey Concentrate, DG = Dextrose Greens, FC = Filter Concentrate, GSR = Glucose Syrup Retentate, N/A = Not Available, MPP = Milk Permeate Powder, PAM = Palatinose Molasses, RWJP = Rinsing Water from Jam Production, SPEC = Specification, TM = Total Mass, VAL = Value, WPP = Whey Permeate Powder.

[a] Data according to supplier.

[b] Gravimetric analysis of the evaporation residues.

It should be noted that food processing wastes and by-products vary in their composition depending on origin, processing conditions, processing parameters, etcetera. According to Weiss and St-Pierre (2009), by-products can be classified as moderately variable, while waste materials are expected to have high variability, even if they originate from the same source. However, such variability of each material tested is not reflected within the study, possibly affecting the interpretability and generalizability of the results.

2.2.3 Laboratory Experiments

2.2.3.1 Standard Proctor Compaction Test

Several studies have shown that additives influence the OMC and related MDD of soils (Tingle and Santoni 2003; Ding et al. 2018; Singh and Das 2020). Therefore, in this study each soil-additive sample was compacted to achieve the OMC and related MDD of the tested soil-additive mixture. Proctor compaction tests were conducted for each concentration and corresponding additive according to DIN 18127:2012-09. Such a procedure ensured that UCS tests were completed on comparable materials.

2.2.3.2 Specimen Preparation for UCS Testing

Each specimen was prepared following the four steps: (1) additive preparation, (2) soil-additive mixing, (3) moulding and compaction, and (4) curing. For this study, two additive concentrations (2 wt% and 4 wt% by dry soil weight) were tested with three replicates for each concentration. The additive concentrations were selected because they have already been used in previous studies for similar substances and soils. Uniform concentrations were chosen due to time constraints. Water-treated soil was set up as a control group. To achieve the MDD of the soil, each specimen was compacted with the OMC.

Additive preparation

In general, by-products and waste materials of the food industry exist in both liquid and solid phases. To guarantee the comparability of the results, the additive concentration refers to the dry mass of the substance.

Soil-additive mixing

After calculating the required quantities of water and additive, the biomaterial was dissolved in the solvent using a magnetic stirrer. The prepared solution was then mixed into the soil in increments until a homogenous mixture was achieved.

Molding and compaction

The material was compacted in a cylindrical 10-cm-diameter x 12-cm-high standard mould (acc. to DIN 18127:2012-09) by a load of 2.5 kg falling 25 times. Three-layered compaction was used to achieve uniform material properties, which is critical for producing comparable results. Figure 2-3 shows the cylindrical mould and the prepared specimen.

Curing

The compacted specimen was placed in a drying oven at a temperature of 40 °C for 7 days to harden the soil-additive matrix.

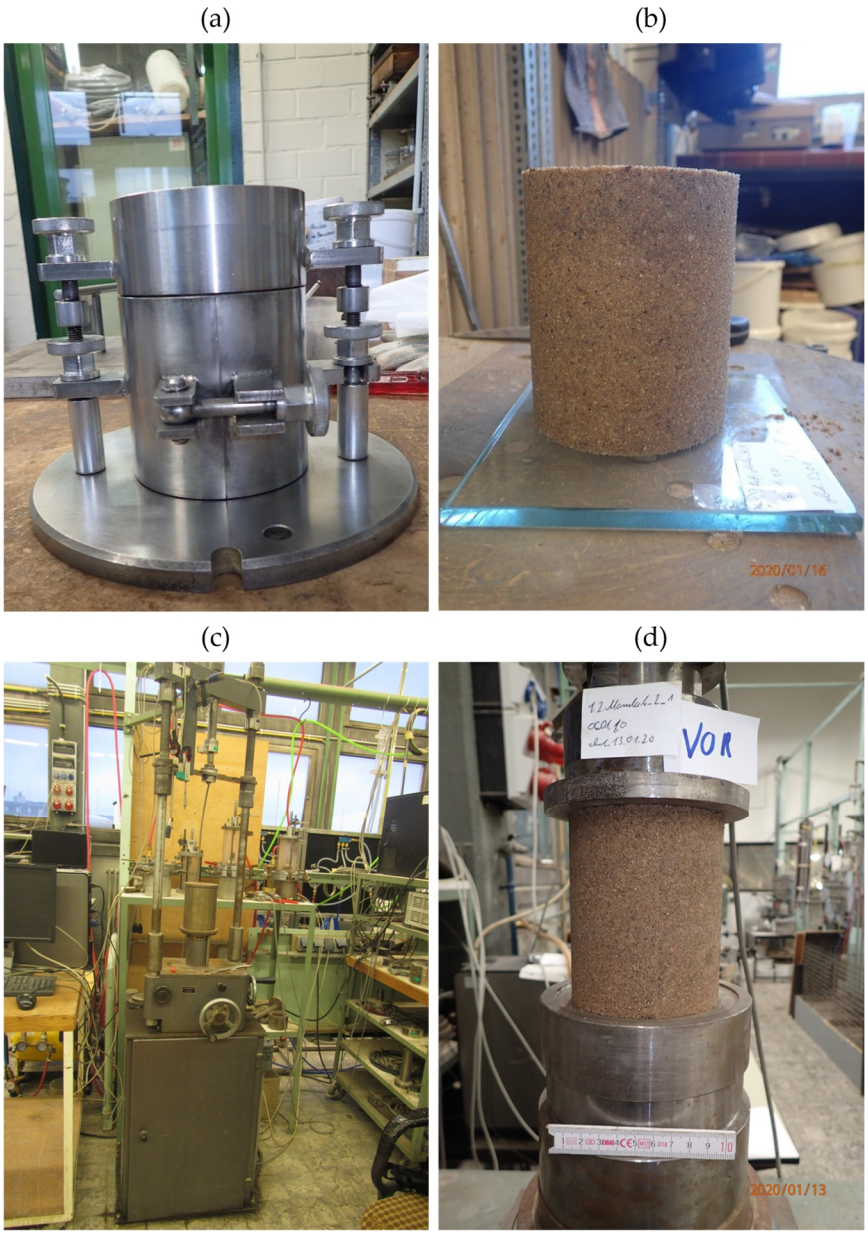


Figure 2-3. Experimental setup of the UCS test: **(a)** cylindrical standard mould, **(b)** prepared UCS sample, **(c)** Wykeham Farrance standard triaxial system, and **(d)** UCS sample under load.

2.2.3.3 UCS test

A Wykeham Farrance standard triaxial system was used with a constant loading rate of 0.25 mm/min (Figure 2-3c). All specimens were tested to failure, or until the maximum strain of 15 % to 20 % was reached (acc. to DIN EN ISO 17892-7:2018-05). The UCS is defined as the maximum axial compressive stress (σ_v) that a cylindrical sample of soil can bear under unconfined conditions (DIN EN ISO 17892-7:2018-05). For each configuration, the mean and the standard deviation were calculated.

2.3 Results

2.3.1 Compaction Characteristics

OMC and MDD data of each Proctor compaction test are given in Table 2-5. Compared to control samples, the addition of biogenic wastes and by-prod-

ucts reduced the OMC and increased the MDD of the soil. Only concentrated distillers solubles did not follow this trend, which increased the OMC from 9.7 % to 9.8 %, while the MDD increased from 1.741 g/cm³ to 1.798 g/cm³. Among the tested substances, whey permeate powder and milk permeate powder had the lowest OMC with 5.7 % and 5.0 %, respectively. Significant changes of the MDD were achieved by whey permeate powder and beet vinasses with a MDD of 1.845 g/cm³ and 1.847 g/cm³.

Table 2-5. Results of the standard Proctor compaction test showing the OMC and the MDD of soils treated with additives at 2 wt% and 4 wt% concentrations (soil dry weight).

Substance	Additive concentration (wt%)			
	2	4	2	4
	OMC (%)		MDD (g/cm³)	
Apple molasses	8.9	6.7	1.826	1.810
Beet molasses	6.9	8.1	1.778	1.800
Beet vinasses	8.1	8.6	1.785	1.847
Chicory molasses	7.7	6.3	1.744	1.754
Chicory vinasses	7.7	7.4	1.769	1.793
Concentrated distillers solubles	9.8	N/A [b]	1.798	N/A [b]
Corn steep liquor	6.0 [a]	N/A [b]	N/A [a]	N/A [b]
Decantation syrup	7.7	7.3	1.761	1.798
Deproteinized whey concentrate	7.5	6.9	1.774	1.789
Dextrose greens	7.1	8.5	1.775	1.828
Filter concentrate	5.9	6.8	1.785	1.773
Glucose syrup retentate	7.8	N/A [b]	1.784	N/A [b]
Milk permeate powder	6.1	5.0	1.754	1.811
Palatinose molasses	8.5	8.3	1.778	1.805
Rinsing water from jam production	8.3	N/A [b]	1.779	N/A [b]
Whey permeate powder	5.6	5.7	1.845	1.837

Note. Abbreviations: MDD = Maximum Dry Density, N/A = Not Available, OMC = Optimum Moisture Content.

[a] A compaction curve could not be established. In this case, the previous moisture content was selected prior to the point where water drained from the Proctor mould during compaction.

[b] Compaction curve could only be determined for 2 wt% additive concentration due to the low dry matter content.

Changing additive concentrations resulted in changes of OMC and MDD values in the treated soils. With the increase of chicory molasses concentration, the OMC decreased from 7.7 % to 6.3 % and the MDD slightly increased from 1.744 g/cm³ to 1.754 g/cm³. By contrast, the OMC and MDD of beet molasses increased from 6.9 % to 8.1 %, respectively, from 1.778 g/cm³ to 1.800 g/cm³. Filter concentrate again performed differently, with an increase of the OMC from 5.9 % to 6.8 % and a reduction of the MDD from 1.785 g/cm³ to 1.773 g/cm³. The compaction curves of all specimens are presented in Figures A-1 to A-15 of Appendix A.

2.3.2 Effect of Additive Type on Soil Strength

Figure 2-4 presents the results of the UCS test of soils treated with 2 wt% and 4 wt% additive solutions. A statistical summary of the UCS test data is given in Table A-1 of Appendix A.

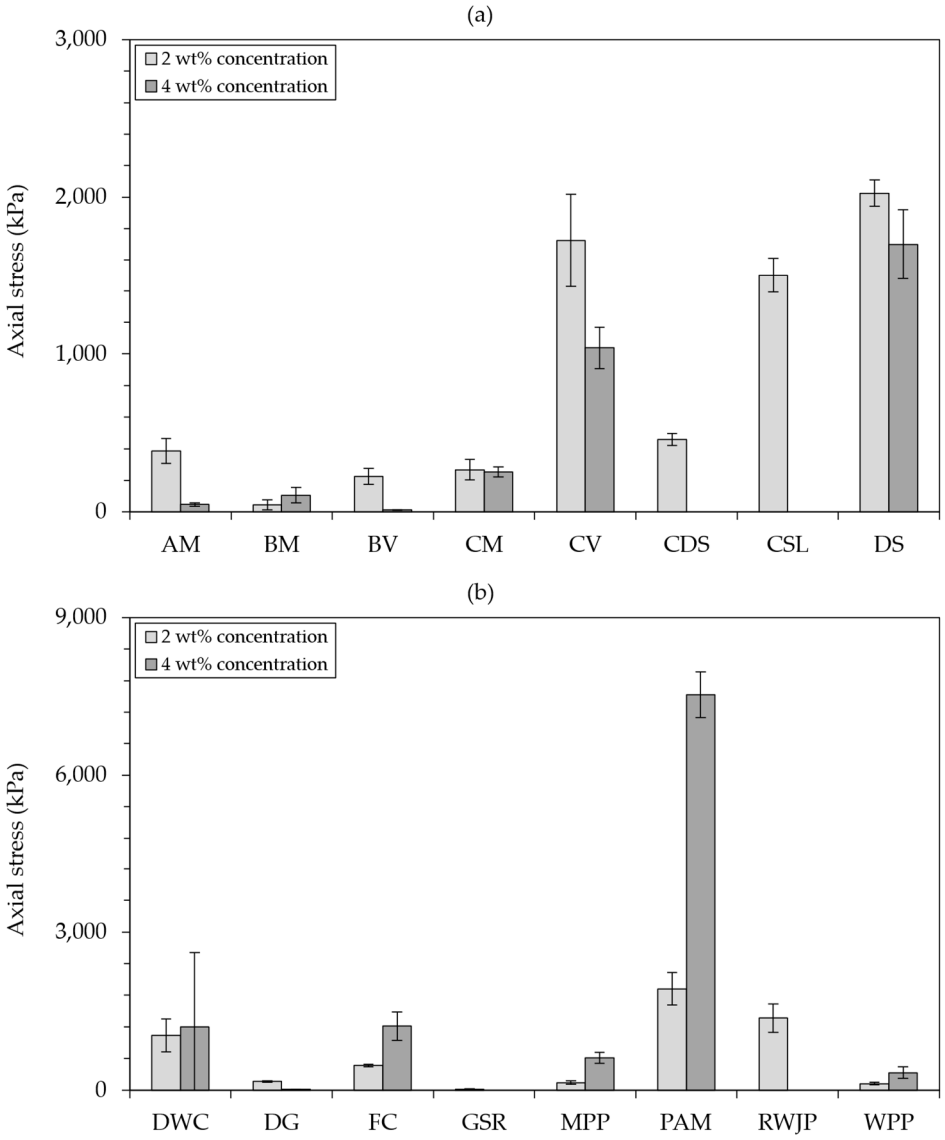


Figure 2-4. Unconfined compressive strength for sand treated with different food processing wastes and by-products (mean, error bars indicate the standard deviation, n = 3): **(a)** apple molasses, beet molasses, beet vinasses, chicory molasses, chicory vinasses, concentrated distillers solubles, corn steep liquor, and decantation syrup, and **(b)** deproteinized whey concentrate, dextrose greens, filter concentrate, glucose syrup retentate, milk permeate powder, palatinose molasses, rinsing water from jam production, and whey permeate powder. Note that the control group, water-treated soil, achieved an UCS of 11 kPa. Abbreviations: AM = Apple Molasses, BM = Beet Molasses, BV = Beet Vinasses, CM = Chicory Molasses, CV = Chicory Vinasses, CDS = Concentrated Distillers Solubles, CSL = Corn Steep Liquor, DS = Decantation Syrup, DWC = Deproteinized Whey Concentrate, DG = Dextrose Greens, FC = Filter Concentrate, GSR = Glucose Syrup Retentate, MPP = Milk Permeate Powder, PAM = Palatinose Molasses, RWJP = Rinsing Water from Jam Production, WPP = Whey Permeate Powder.

The studied biogenic wastes and by-products had different effects on the mechanical strength of the treated substrate. While some of the substances significantly im-

proved the UCS of the soil, others had little or no impact on its geotechnical behavior. The control group, soil treated with pure water, showed an UCS of 11 kPa (*SD = 1*). Negligible improvement in the mechanical strength was achieved by glucose syrup retentate that increased the UCS to 15 kPa (*SD = 5*). Beet molasses, dextrose greens, beet vinasses and chicory molasses were slightly more effective, which improved the UCS to 106 kPa (*SD = 49*), 161 kPa (*SD = 17*), 225 kPa (*SD = 50*) and 267 kPa (*SD = 66*), respectively. By adding milk permeate powder, the UCS almost doubles from 327 kPa (*SD = 109*) to 609 kPa (*SD = 102*) in comparison to whey permeate powder. Apple molasses und concentrated distillers solubles showed an improved UCS of 385 kPa (*SD = 80*) and 457 kPa (*SD = 38*). Deproteinized whey concentrate and filter concentrate demonstrated a similar effect on the mechanical strength of the soil, which achieved a UCS of 1,201 kPa (*SD = 1403*), respectively, 1,213 kPa (*SD = 274*). Rinsing water from jam production, corn steep liquor, chicory vinasses and decantation syrup significantly improved the mechanical behavior of the soil and increased the UCS to 1,366 kPa (*SD = 268*), 1,502 kPa (*SD = 109*), 1,723 kPa (*SD = 294*) and 2,026 kPa (*SD = 83*), respectively. Palatinose molasses was by far the most effective in strength improvement of the soil among the tested substances with a UCS of 7,535 kPa (*SD = 436*). The stress-strain curve of each specimen is presented in Figures A-16 to A-30 of Appendix A.

2.3.3 Effect of Additive Concentration on Soil Strength

Modifying the concentration of the studied biomaterials had different effects on the mechanical strength of the soil (Figure 2-4). An increase of the additive quantities from 2 wt% to 4 wt% resulted in both an improvement and a deterioration of the UCS. For decantation syrup, increasing its amount decreased the UCS from 2,026 kPa (*SD = 83*) to 1,699 kPa (*SD = 221*). Chicory vinasses at 4 wt% was less effective than chicory vinasses at 2 wt% that reduced the soil strength from 1,723 kPa (*SD = 294*) to 1,038 kPa (*SD = 131*). With an increase in the concentration of apple molasses, a significant reduction of the UCS from 385 kPa (*SD = 80*) to 47 kPa (*SD = 10*) was observed. Soil treated with beet vinasses and dextrose greens showed a similar behavior, with the UCS deteriorating from 225 kPa (*SD = 50*) to 12 kPa (*SD = 1*), respectively, from 161 kPa (*SD = 17*) to 15 kPa (*SD = 2*). By contrast, 4 wt% beet molasses increased the UCS from 46 kPa (*SD = 32*) to 106 kPa (*SD = 49*) compared to 2 wt% beet molasses. Milk permeate powder and whey permeate powder also showed that an increase in concentration improved the mechanical strength of the soil. Their UCS increased from 141 kPa (*SD = 34*) to 609 kPa (*SD = 102*), respectively, from 121 kPa (*SD = 22*) to 327 kPa (*SD = 109*). Soil treated with 4 wt% filter concentrate was more effective than 2 wt% filter concentrate that improved the soil strength from 465 kPa (*SD = 21*) to 1,213 kPa (*SD = 274*). Palatinose molasses significantly improved the UCS from 1,918 kPa (*SD = 308*) to 7,535 kPa (*SD = 436*) by increasing the concentration. Increasing the amount of deproteinized whey concentrate and chicory molasses showed negligible effect on mechanical soil strength, with UCS increasing from 1,037 kPa (*SD = 316*) to 1,201 kPa (*SD = 1403*) and with UCS decreasing from 267 kPa (*SD = 66*) to 253 kPa (*SD = 32*), respectively.

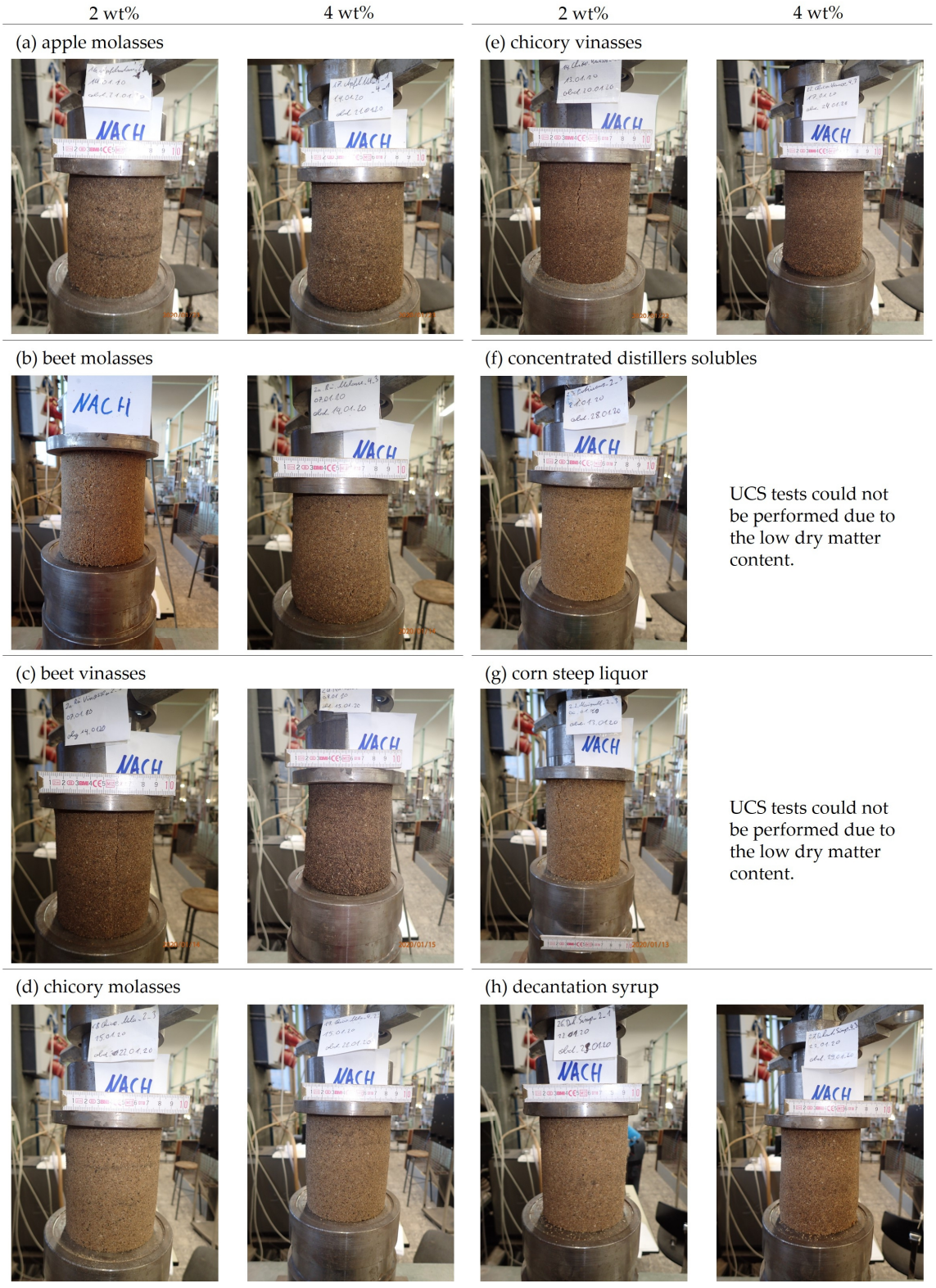


Figure 2-5. Failure characteristics of reinforced specimens: **(a)** apple molasses, **(b)** beet molasses, **(c)** beet vinasses, **(d)** chicory molasses, **(e)** chicory vinasses, **(f)** concentrated distillers solubles, **(g)** corn steep liquor, and **(h)** decantation syrup.

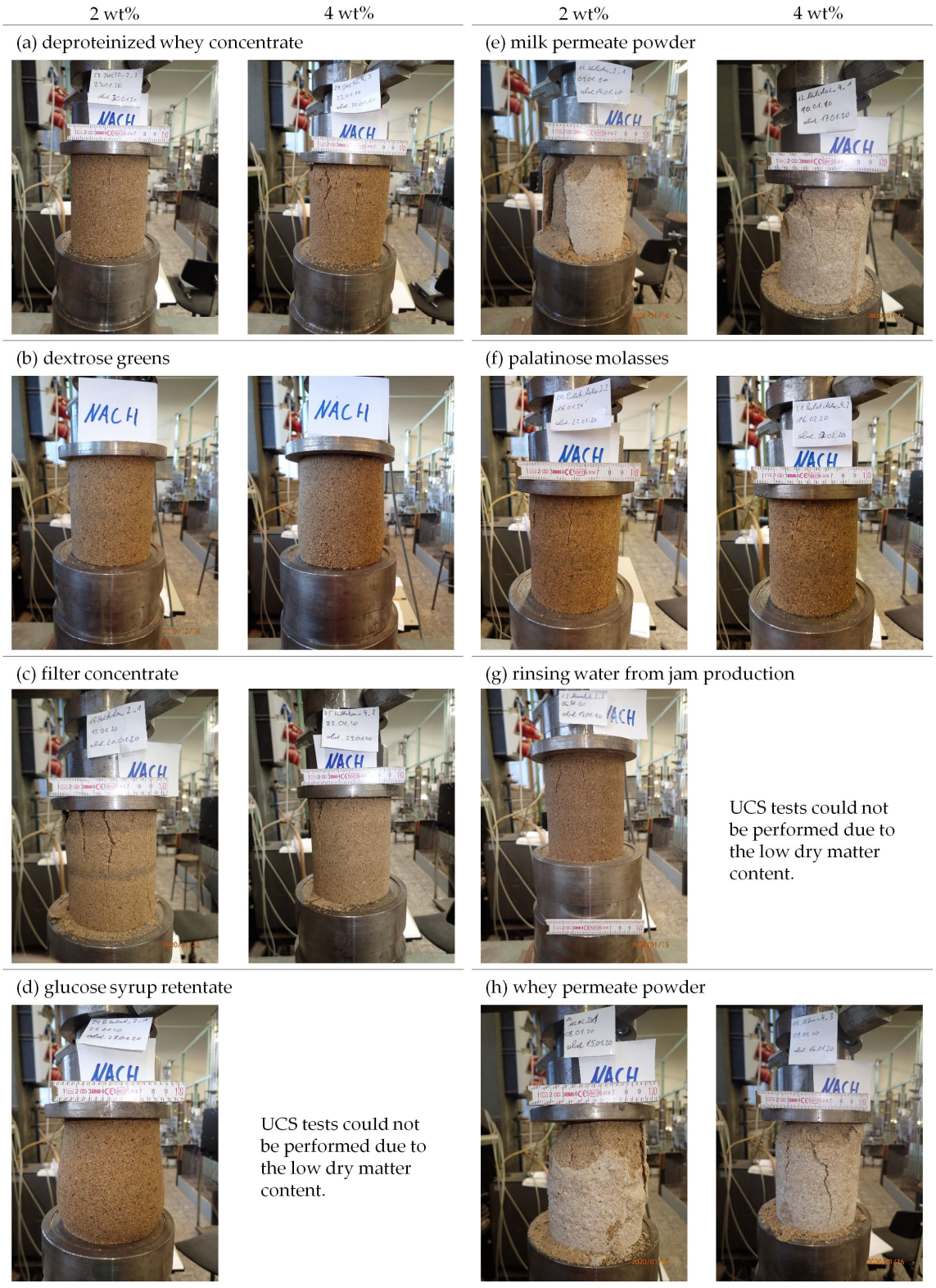


Figure 2-6. Failure characteristics of reinforced specimens: **(a)** deproteinized whey concentrate, **(b)** dextrose greens, **(c)** filter concentrate, **(d)** glucose syrup retentate, **(e)** milk permeate powder, **(f)** palatinose molasses, **(g)** rinsing water from jam production, and **(h)** whey permeate powder.

2.3.4 Failure Characteristics

Figures 2-5 and 2-6 present typical visual failure characteristics of treated specimens upon UCS testing. Soil treated with chicory molasses, apple molasses, beet molasses, beet vinasses, dextrose greens and glucose syrup retentate showed a ductile fracture behavior. The specimens bulged in the lower and the upper third. Specimens with 4 wt% chicory vinasses and 4 wt% decantation syrup demonstrated a similar effect on the fracture behavior of the treated soil. Specimens with 2 wt% chicory vinasses, 2 wt% decantation syrup, palatinose molasses, rinsing water from jam production, corn steep liquor and concentrated distillers solubles failed under axial stress by developing slight vertical cracks mainly in the upper third of the sample body. Despite crack formation, the specimens demonstrated high stability and were able to retain their shape while being removed from the UCS testing machine. An addition of 4 wt% whey permeate, filter concentrate, and deproteinized whey concentrate led to increasing brittleness. The specimens showed strong vertical cracks with larger fragments breaking out of the soil-additive matrix, and some samples indicated total failure. The specimens of milk permeate powder and 2 wt% whey permeate showed strong spalling in the upper third of the body and formed either vertical cracks or failed in total. The specimens were generally brittle and fragile.

2.4 Discussion

2.4.1 Compaction Characteristics

Results of the standard Proctor compaction test have shown that biogenic wastes and by-products from the food processing industry have different effects on the OMC and MDD of the investigated soil (Table 2-5). Effects vary with the type of additive and their applied concentration. Thus, this needs to be considered when preparing specimens for UCS test to obtain comparable results. Such findings agree with the results of Tingle and Santoni (2003), who tested seven non-traditional soil stabilizers at varying concentrations and observed both an increase and a decrease of the OMC and MDD.

Moreover, the data demonstrate that the chosen additives reduced the OMC and increased the MDD of the soil. According to Proctor's theory (1933), the increase in MDD could be due to the added solution acting as a lubricant and reducing the frictional and capillary forces between soil particles. The enhanced lubrication enables the rearrangement of soil grains into a denser structure and thus increases the dry density.

2.4.2 Effect of Additive Type on Soil Strength

Results of this study also demonstrate that the chosen wastes and by-products increase the UCS of coarse sandy soil and improve its geotechnical behavior. The observed increase in mechanical strength is possibly a result of the added low-molecular carbohydrates, polysaccharides and proteins contained in the tested substances, which establish and enhance bonds between single soil particles through adhesive and cohesion forces. Adhesion is directly linked to molecular interactions at the interface of two phases, and thus between the soil particle and the additive. By contrast, cohesion refers to the internal strength of a material. By curing the specimen, the additive sets and achieves its cohesive strength that hardens the soil-additive matrix.

Palatinose molasses and decantation syrup achieved the highest strength improvement (Figure 2-4). These results are unexpected, as previous studies only investi-

gated polysaccharides and proteins as biodegradable soil stabilizers and not low-molecular carbohydrates (Blanck et al. 2014; Ayeldeen et al. 2017; Soldo et al. 2020; Chang et al. 2018). Palatinose molasses includes predominantly isomaltulose (α-1,6 linked) and trehalulose (α-1,1 linked) with minor constituents of sucrose (α-1,2 linked), isomaltose (α-1,6 linked), fructose and glucose (Table 2-4). By contrast, decantation syrup is mainly composed of sucrose, but also contains small proportions of glucose, fructose and oligosaccharides with a degree of polymerization of three (Table 2-4).

Glucose syrup retentate, beet molasses, dextrose greens and chicory molasses, whose dominant components (glucose, fructose and sucrose) are comparable to decantation syrup, had only a little or no impact on the geotechnical behavior of the soil (Figure 2-4). The ductile fracture behavior of the specimens (Figures 2-5 and 2-6) might suggest that the mono- and disaccharides transferred predominantly into an amorphous state rather than those contained in the decantation syrup. Amorphous carbohydrates are highly hygroscopic, with the effect that they absorb moisture from the environment (Wrolstad 2012). Hence, it is assumed that the absorbed water decreases the cohesive strength of the additive, reducing the inter-particle bonding and increasing the plasticity of the soil. However, it is unclear why more crystalline than amorphous lattice structures were formed in the specimens treated with decantation syrup under identical conditions. Contrary to this, milk permeate powder (MPP) and whey permeate powder (WPP), rich in lactose (β-1,4 linked), produced a higher UCS but with the formation of a brittle fracture. The brittleness appears to indicate that lactose has changed into a crystalline state and not into an amorphous state. Thus, the mechanical strength of the specimen increases. However, the differences in UCS between MPP and WPP are unclear, although both have almost the same material composition (i.e., MPP: 85 % lactose, 2.5 % protein and max. 1 % fat in DM; WPP: 84 % lactose, 2.7 % protein and max. 1 % fat in DM (Table 2-4)).

As expected, protein- and polysaccharide-containing wastes and by-products significantly increased the UCS of the soil. This finding is consistent with the results of Chang et al. (2015a), Ayeldeen et al. (2017), and Chang et al. (2018), who demonstrated that biopolymers are capable of enhancing the mechanical strength of soils. Biopolymers have the ability to form three-dimensional networks by linking polymer chains through covalent or non-covalent bonds (Azeredo and Waldron 2016). These network structures create bonds between the single soil particles and improve the geotechnical behavior of soils (Chen et al. 2016). However, the UCS test indicated a reduced UCS for those specimens treated with beet vinasses, concentrated distillers solubles and chicory molasses despite their high biopolymer content (Figure 2-4). A possible explanation of these results could be that the contained biopolymers feature a low degree of crystallinity and cross-linking. Khatami and O'Kelly (2013) state that a high degree of crystallinity and/or cross-linking contributes to high soil strength. It is assumed that the contained glucose, fructose and sucrose also effect the mechanical performance of the soil, which weaken the inter-particle bonding due to their tendency to hygroscopy (Wrolstad 2012). Hence, the UCS of the specimens decreases.

2.4.3 Effect of Additive Concentration on Soil Strength

The UCS test showed that an increase in additive concentration enhanced and reduced mechanical soil strength. Such results indicate that a particular dosage of the tested reagents leads to optimal soil strength (as established by the UCS test) and that

this concentration depends on the type of additive. These findings concur with those of Blanck et al. (2014), who demonstrate that soil treated with 2 wt% lignosulfonate achieves a higher UCS compared to a concentration of 0.5 wt% or 5 wt%. Soldo et al. (2020) concluded that each biopolymer-reinforced soil has an optimum biopolymer concentration, which differs depending on the biopolymer type. Hence, this needs to be considered when using UCS values as an indicator for evaluating reagents regarding their dust control potential.

Results of this study show either reduced or enhanced UCS values with increasing additive concentration (Figure 2-4). Such completely different responses to additive concentrations may be explained by the composition of the tested biomaterials. The chosen additives comprise mixtures of different substances with different physical and chemical properties. Thus, observed decreases in UCS values with increasing concentration might be due to changes in viscosity upon soil treatment. Also, Nair and Kannan (2020) state that the UCS of biopolymer-treated soil decreases beyond the optimum concentration due to the increased viscosity, which contributes to a reduced bonding between soil particles and the stabilizer. For apple molasses, beet vinasses, chicory molasses and dextrose greens, rich in glucose, fructose and sucrose, there might be another explanation. As amorphous carbohydrates are highly hygroscopic (Wrolstad 2012), an increase in concentration enhances the absorption of moisture from the environment, thus weakening the bonding between the particles and decreasing the mechanical strength of the soil. However, beet molasses did not follow that trend (Figure 2-4), whereby the UCS value increased with increasing concentration, although its primary components are hygroscopic low-molecular carbohydrates.

2.4.4 Comparison of Food Processing Wastes and By-Products to Other Biopolymers

In previous studies, various biopolymers have been investigated to enhance the mechanical strength of sandy soils, with polysaccharides being the primary focus (Table 2-6). By comparison, laboratory experiments of this study have revealed similar or even higher UCS values for soils treated with food processing wastes and by-products (Figure 2-4). At a concentration of 4 wt%, palatinose molasses achieved a UCS of 7,535 kPa. Only 4 wt% xanthan gum obtained a comparable UCS of 7,087 kPa (Soldo et al. 2020). The UCS values of rinsing water from jam production (σ_v: 1,366 kPa), corn steep liquor (σ_v: 1,502 kPa) and chicory vinasses (σ_v: 1,723 kPa) are in a similar range as casein and sodium caseinate with an UCS of approx. 1,550 kPa, respectively, of approximately 1,700 kPa (Fatehi et al. 2018). By comparison, filter concentrate, which also consists of proteins from the dairy industry, achieved a slightly reduced UCS of 1,213 kPa. Soil treated with 2 wt% decantation syrup showed a comparable mechanical strength as alginate and agar gum with an UCS of 2,044 kPa, respectively, of approximately 2,300 kPa (Chang et al. 2015c; Soldo et al. 2020).

However, a direct comparison of this study's UCS test data with those of other works testing biodegradable reagents is difficult to achieve because there are considerable differences in the experimental designs. Also, Huang et al. (2008) and Elkady (2015) indicated that stabilizers enhance the UCS of soils by a longer curing time and an increase in curing temperature. Furthermore, selected concentration and tested soil type influence the strength improvement induced by the stabilizer, thus hindering the comparability of UCS results (Latifi et al. 2016; Tingle and Santoni 2003).

Table 2-6. Published UCS test results for sandy soils treated with biopolymers.

Biopolymer	UCS (kPa)	UCS soil (kPa)	Concentration (wt%)	Soil type	Curing temperature (°C)	Curing time (d)	Reference
Agar gum	2,300 [a]	< 10	3	SP–SM	18–22	28	Chang et al. (2015c)
Alginate	2,044	1,169	2	SW-SM	N/A	30	Soldo et al. (2020)
Alkali lignin	2,500 [a]	n/a	5	SP	100	1	Yang et al. (2018)
Beta-1,3/1,6-glucan	2,467	1,169	4	SW-SM	N/A	30	Soldo et al. (2020)
Casein	1,550 [a]	0	5	SP	21–25	14	Fatehi et al. (2018)
Chitosan	1,401	1,169	2	SW-SM	N/A	30	Soldo et al. (2020)
Gellan gum	435	n/a	2	SP	20	28	Chang et al. (2016a)
Guar gum	3,277	1,169	4	SW-SM	N/A	30	Soldo et al. (2020)
Sodium caseinate	1,700 [a]	0	5	SP	21–25	14	Fatehi et al. (2018)
Xanthan gum	7,087	1,169	4	SW-SM	N/A	30	Soldo et al. (2020)

Note. The soil type was classified according to the Unified Soil Classification System. Abbreviations: SP–SM = Poorly graded sand with silt, SW-SM = Well-graded sand with silt, SP = Poorly graded sand.

[a] The value was derived from a graph.

2.4.5 *Application Potential of Food Processing Wastes and By-Products as Dust Suppressants*

UCS test data is a widely applied evaluation indicator for dust suppressants intended for applications on exposed mine soils (Xu et al. 2018). A higher UCS value reflects reinforced bonding between soil particles, implying increased resistance against aerodynamic drag and lift forces. Ding et al. (2018) quote that an increased UCS value indicates an enhanced dust suppression effectiveness. Consequently, palatinose molasses, decantation syrup, chicory vinasses, corn steep liquor and rinsing water from jam production have the highest application potential as dust suppressants among the tested biogenic wastes and by-products, with palatinose molasses being the most promising. By contrast, the potential of filter concentrate and deproteinized whey concentrate is considered to be lower, although both reagents achieved similar high UCS values (Figure 2-4). The brittle failure characteristics appear to suggest that filter concentrate and deproteinized whey concentrate form inflexible and brittle crusts upon surface treatment. Such crusts are more prone to erosive forces and indicate a reduced potential for long-term dust control (Gillies et al. 1999). Also, a lower application potential exists for milk permeate powder and whey permeate powder, as the specimens showed brittle fracture behavior and achieved a reduced UCS value (Figures 2-4, 2-5 and 2-6). By comparison, the potential of apple molasses and concentrated distillers solubles might be higher, although they had a similar UCS value. The reason for this is that both reagents failed more ductile under axial stress. Hence, it can be concluded that they are more likely to form a malleable crust, which may not be as susceptible to external factors as brittle crusts.

The UCS test results indicate that glucose syrup retentate, beet molasses, dextrose greens, beet vinasses and chicory molasses have the lowest application potential, as they only slightly increased the mechanical strength of the soil. These findings partially contradict scientific publications and best practice guides that state beet molasses as a widely applied dust suppressant. (Omane et al. 2017; Piechota et al. 2004; Thompson and Visser 2007; Bolander and Yamada 1999). A possible explanation for this non-conformity might be the selected additive concentration, which deviates from the optimal concentration, thus falsifying the result. Moreover, food processing wastes and by-products generally show variations in their composition, possibly affecting the interpretability of the UCS test results (Weiss and St-Pierre 2009). Hence, future research is required to explore such variability and re-evaluate reagents assessed with low application potential.

2.4.6 Possible Applications of Food Processing Wastes and By-Products as Dust Suppressants at Mine and Mineral Processing Sites

This study demonstrates that food processing wastes and by-products have the potential to abate fugitive dust emissions at mine and mineral processing sites. Here, there are several application sites where the studied biomaterials can be used as dust suppressants. Possible applications include benches, bare grounds, dry tailings basins, waste rock heaps, ore stockpiles or overburden dumps. Moreover, the biomaterials could potentially be used for reducing dust emissions from unpaved roads and agricultural lands (e.g., abandoned fields).

There are generally two approaches how dust suppressants can be applied to mine soils. The additives are dissolved in water and then either applied topically, respectively, sprayed on the substrate surface or mixed into the first layer of the substrate (Edvardsson 2009). For barren surfaces that are primarily affected by wind erosion, a topical treatment is usually sufficient. By contrast, for accessible areas, which must withstand traffic erosion, it is recommended to incorporate the biomaterial into the aggregate (Piechota et al. 2004). Although the so-called mixed-in-place method entails a greater expense, it is generally more economical than topical treatments due to the increased longevity and the associated reduced re-application intervals (Jones 2017; Thompson and Visser 2007; Rushing and Tingle 2007). This means, however, that this method should be used primarily for areas with a long lifetime to exploit the cost advantage fully (Piechota et al. 2004).

Wastes and by-products from food production and processing are biodegradable and considered cost-effective. Consequently, their application as dust suppressants would reduce dust control costs and minimize the use of commercially available products that may harm the environment. Moreover, their contained carbohydrates and proteins may activate the bacterial life in soils and stimulate root activity and plant growth (Colla et al. 2014; Wilson et al. 2018; Kume et al. 2002). Several studies already demonstrated that biopolymers foster seed germination and the growth of vegetation in soils (Chang et al. 2015d; Chang et al. 2020; Pylak et al. 2019). This might be of particular interest for revegetation activities of abandoned waste heaps and dry tailings basins from former mining operations. Here, inherent physical and chemical properties of the stored waste materials and processing residues may limit plant growth due to nutrient and organic matter deficiencies, low water retention, lack of texture and structure and high alkalinity (Jones et al. 2010; Smith and Underwood 2000). Hence, the applied bio-

materials would act as fertilizer and stabilize substrates (i.e., soil and seed) against erosive forces until a plant cover has been established. However, it should be noted that the application of food processing wastes and by-products as dust suppressants may also have potential adverse effects. For example, Bolander and Yamada (1999) reported that sugar-based treatments could attract animals and insects at the application sites. Moreover, heavy rainfall events may leach the water-soluble biomaterials through soils into freshwater bodies. Organic matter in aquatic systems increases bacteria and other microorganisms' growth, which reduces the availability of dissolved oxygen, thus impairing aquatic habitats and biodiversity (Ferreira et al. 2017). Potential hazards may also arise from the anaerobic degradation of the tested biomaterials, releasing gases such as carbon dioxide, methane or sulphur compounds. However, there is no evidence in the literature that the application of biodegradable dust suppressants (e.g., biopolymers, lignosulfonates) leads to problems with gaseous pollutants at typical application rates. Dust suppressant solutions (0.05 to 0.12 kg/L) are typically applied at application rates of 1.4 to 4.5 L/m² (Piechota et al. 2004).

2.4.7 Limitations of the Study

The study results indicate a potential of wastes and by-products from the food industry as dust suppressants intended for applications on exposed mine soils. However, these results must be interpreted with caution, and a number of limitations should be borne in mind. (1) The UCS test is an evaluation method that allows only indirect conclusions regarding the dust control performance of a reagent, and its significance depends on the type of additive to be tested (Xu et al. 2018). Consequently, laboratory-based wind tunnel tests need to be conducted to evaluate the actual dust control effectiveness of the tested reagents. In addition, field trials are required to establish their effectiveness under actual field conditions, indicating potential commercial-scale application. (2) Caution should be exercised when transferring the results to unpaved roads because the focus of the study was to assess the biomaterials' potential in suppressing dust emissions from exposed mine soils, where mainly wind erosion rather than the abrasive forces of vehicles contribute to dust generation. (3) The biomaterials were tested with two uniform additive concentrations due to time constraints. However, probably each biomaterial has its optimal concentration, which may distort the results. (4) The specimens were cured in a drying oven at a temperature of 40 °C for 7 days. Such curing settings do not correspond to any field applications. Environmental conditions at mine and mineral processing sites are likely to impair the effect of the tested biomaterials on soil strength. (5) The transferability of the results to other mine soils with different grain size distributions is limited because the soil type can influence the strength improvement induced by the additive (Tingle and Santoni 2003; Latifi et al. 2016).

2.5 Conclusions

This study investigated the potential of sixteen biodegradable wastes and by-products from the food processing industry to control dust emissions from sandy soils. The following conclusions can be drawn from the experimental results:

- UCS tests showed that rinsing water from jam production (σ_v: 1,366 kPa), corn steep liquor (σ_v: 1,502 kPa), chicory vinasses (σ_v: 1,723 kPa), decantation syrup (σ_v: 2,026 kPa) and palatinose molasses (σ_v: 7,535 kPa) significantly improved the mechanical strength of the substrate (σ_v: 11 kPa), thus indicating a strong potential

of these biomaterials as dust suppressants. Palatinose molasses and decantation syrup achieved the highest UCS values.

- Protein- and polysaccharide-containing substances obtained on average higher UCS values than low-molecular carbohydrates due to the formation of three-dimensional network structures.
- The data indicate a low potential for substances with high glucose and fructose content, as they had minor or no impact on soil strength.

This study demonstrates that carbohydrate- and protein-rich wastes and by-products from the food industry have the potential to be applied as dust suppressants at mine sites. Such approaches would foster environmentally benign dust control measures of large, exposed areas at mine sites and provide new markets for the food processing industry for its wastes and by-products.

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Chapter 3
Ability to Modify Soil Surfaces to Resist Wind Erosion

A version of this chapter has been published as a preprint on SSRN entitled "Effectiveness of food processing by-products in suppressing wind-induced dust emissions from mine soils: Results from laboratory wind tunnel experiments". SSRN is an open-access repository that facilitates the rapid dissemination of research, ensuring immediate accessibility for scholars and the broader public. It should be noted that this preprint has not yet undergone the peer-review process.

Published	16 September 2022
Authors	Justus Freer, Johannes L. Sieger, Bernd G. Lottermoser and Marius Braun
Citation	Freer, J.; Sieger, J. L.; Lottermoser, B. G.; Braun, M. (2022): Effectiveness of food processing by-products in suppressing wind-induced dust emissions from mine soils. Results from laboratory wind tunnel experiments. Available online at https://ssrn.com/abstract=4220674.

3.1 Introduction

Mine soils are susceptible to wind erosion, which leads to emissions of mineral dust particles and associated contaminants into ambient air, and consequently to adverse effects on human health and the environment (e.g., air and water pollution, visibility nuisance, respiratory and cardiovascular ailments) (Du et al. 2016; Du Plessis et al. 2016; Gautam et al. 2016; Manisalidis et al. 2020; Ghose 2004). Soil particles become airborne, when the aerodynamic forces overcome resistive forces (i.e., gravity and interparticle forces) (Shao and Lu 2000). Such wind-induced dust substantially contributes to overall particulate concentrations at and around mine and mineral processing sites (Mpanza et al. 2020; Oguntoke et al. 2013; Mwaanga et al. 2019; Ghose and Majee 2000). For example, Chang et al. (2010) demonstrated that wind erosion of bare grounds could cause up to 40 % of total suspended particulate at gravel processing sites. Hence, measures that control wind erosion are mandatory for the mining industry to comply with legal air quality standards.

A practical method for wind erosion control and dust mitigation is the application of dust suppressants, which modify the surface layer's physical properties to reduce soil erodibility (Piechota et al. 2004; Parvej et al. 2021). Traditional dust suppressants include hygroscopic salts, petroleum resins, polymer emulsions, tar-based products and bitumen emulsions (Thompson and Visser 2007). However, such amendments may have adverse environmental impacts, e.g. induced changes in flora and wildlife populations, changed hydrologic characteristics of soils, or impairment of surface and groundwater quality (Singh et al. 2003; Piechota et al. 2004). Hence in recent years, research has increasingly focused on investigating environmentally benign reagents that may control and suppress dust emissions at industrial sites.

Biopolymers constitute promising alternatives to chemical dust control products as they are renewable, decompose naturally in the environment and have the ability to agglomerate soil particles due to creating three-dimensional network structures and coatings (Azeredo and Waldron 2016; Chen et al. 2016). Research studies using unconfined compressive strength (UCS) tests show that proteins and polysaccharides, both biopolymers, can significantly enhance the mechanical strength of soils, indicative of enhanced wind erosion resistance and thus improved dust suppression effectiveness (Soldo et al. 2020; Chen et al. 2016; Fatehi et al. 2018; Chang et al. 2016a; Xu et al. 2018). However, biopolymers tend to give highly viscous solutions at low concentrations (e.g., xanthan gum), are partially not readily dissolvable in cold water (e.g., gellan gum) or occasionally need pH-modifications to be dissolved (e.g., chitosan) (Mudgil et al. 2014; Chang et al. 2016a; Hataf et al. 2018). This implies that typically employed equipment for dust suppression can probably not be used and must either be modified or developed considering the rheological properties of individual biopolymers (Chang et al. 2020).

The recently published study by Freer et al. (2022a) highlights potential applications of carbohydrate- and protein-rich wastes and by-products from the food industry as eco-friendly dust suppressants at mine sites. Tested materials are biodegradable, inexpensive, readily available and easy to apply. Conducted UCS experiments have revealed that soils treated with such biogenic materials achieve similar or even higher UCS values than soils treated with commercial biopolymers. Chicory vinasses, corn steep liquor, decantation syrup and palatinose molasses proved to be the most promising dust control reagents as they significantly improved the mechanical behavior of sand (i.e.,

high UCS values, ductile fracture characteristics). However, UCS test data only enable indirect conclusions regarding the effectiveness of dust suppressants (Xu et al. 2018). Appropriate experiments such as wind erosion simulation experiments are required to evaluate the actual performance of surface treatments in mitigating fugitive dust.

The present work aimed to evaluate the effectiveness of four food processing by-products (chicory vinasses, corn steep liquor, decantation syrup, and palatinose molasses) as dust suppressants. Laboratory-based wind tunnel experiments were conducted on sandy mine soils treated with aqueous solutions of different additive concentrations and application rates to establish required dosage rates per unit surface area to achieve maximum erosion control. Untreated mine soil and soil only treated with water were prepared as a control group to determine the quantitative dust control effectiveness of applied biomaterials. Hence, this study provides new insights into applying carbohydrate- and protein-based by-products as eco-friendly reagents for dust suppression. Moreover, such research will help mining operators to implement sustainable dust control practices and comply with air quality standards.

3.2 Materials and Methods

3.2.1 Mine Soil

The soil used in this study is classified as a medium-coarse sand (acc. to (DIN EN ISO 14688-1:2018-05)) and has a similar grain size distribution as mine soils and surface exposures of industrial mineral and opencast lignite mines in North-Rhine Westphalia (Germany). The main mineral of the sand is quartz, with minor concentrations of orthoclase, microcline and clinochlore. Additional information on the chemical and physical properties of the test substrate is documented in Freer et al. (2022a).

3.2.2 Studied Materials from Food Processing

Four food processing by-products were analyzed regarding their effects on the erosion behavior of mine soil surfaces: chicory vinasses, corn steep liquor, decantation syrup, and palatinose molasses. Chicory vinasses is a by-product of chicory processing obtained after separating inulin and oligofructose. Its dry matter content consists mainly of crude protein (Freer et al. 2022a). Corn steep liquor represents the concentrated liquid fraction from the steeping process of corn and is composed of carbohydrates and proteins and their derivatives (Caballero 2003). Decantation syrup accumulates during the production of candy sugar that predominantly consists of sucrose and contains small concentrations of fructose, glucose, and oligosaccharides with a polymerization degree of three. Palatinose molasses is defined as the non-crystallized fraction from the production of isomaltulose by enzymatic conversion of sucrose from sugar beets. It primarily includes isomaltulose and trehalulose with secondary components of sucrose, isomaltose, fructose and glucose (Freer et al. 2022a). Additional characteristics of tested amendments are summarized in Tables 3-1 and 3-2.

Table 3-1. Characteristics of tested food processing by-products – part 1 (Freer et al. 2022a).

Substance	Density (g/cm³)	Appearance	Color	Water solubility
CV	1.30	viscous	dark brown	soluble
CSL	1.23	liquid	dark brown	soluble
DS	1.30	viscous	dark brown	soluble
PAM	1.31	viscous	yellow brownish	soluble

Note. Abbreviations: CV = Chicory Vinasses, CSL = Corn Steep Liquor, DS = Decantation Syrup, PAM = Palatinose Molasses.

Table 3-2. Characteristics of tested food processing by-products – part 2 (Freer et al. 2022a).

Sub-stance	pH value	Dry matter (%)		Composition	Supplier
		SPEC	VAL		
CV	3.0–5.0	60.0–70.0	63.3	crude protein (45–51 % in TM)	BENEO-Orafti
CSL	3.5–4.5	25.0–35.0	27.0	crude protein (36–49 % in DM); starch, reducing sugars, crude fiber	Cargill Deutschland
DS	> 5.5	65.0–75.0	72.0	sucrose; glucose; fructose; oligosaccharides	BENEO-Orafti
PAM	> 4.0	62.0–68.0	68.2	Isomaltulose and trehalulose (> 50 % in DM); sucrose, isomaltose, fructose and glucose (28–42 % in DM)	BENEO-Orafti

Note. Abbreviations: CV = Chicory Vinasses, CSL = Corn Steep Liquor, DM = Dry Matter, DS = Decantation Syrup, SPEC = Specification, TM = Total Mass, PAM = Palatinose Molasses, VAL = Value.

3.2.3 Sample Preparation

Each specimen was prepared as follows: (1) additive preparation, (2) application, and (3) curing. Ten additive concentrations (1 to 10 %) and eight application rates (0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3 L/m²) were tested with three replicates each. Untreated soil and soil only treated with water were selected as control group. Initially, additives were dissolved in pure water and mixed with a magnetic stirrer to obtain a homogeneous solution. Please note that the solutions were prepared according to the respective dry matter content of the biomaterials (Table 3-2). Solutions were then topically sprayed on soil surfaces using a hand-held trigger sprayer. Before wind erosion experiments, prepared samples were air-dried for 48 hours at ambient laboratory temperature.

3.2.4 Wind Erosion Experiments

The wind tunnel used in this study consisted of different components to generate a laminar flow: (a) diffuser, (b) honeycomb, (c) two screens, and (d) contraction (Figure 3-1). A Korfmann dGAL4-30/30 axial fan with a diameter of 400 mm driven by a 1.5 kW electric motor was attached to the diffuser. The diffuser had a length of 560 mm and transitioned from a circular cross-section with a diameter of 392.8 mm to a square cross-section of 608 x 608 mm. At the end of the diffusor section, the airflow was passed through a flow conditioning section (i.e., honeycomb-screen combination). The honeycomb was constructed out of 30-mm diameter and 200-mm long plastic tubes that were stacked and glued together. Two square woven steel screens with a mesh size of

0.065 mm were positioned downstream of the honeycomb. In total, the length of the flow conditioning section was 407 mm. The contraction section was 1000 mm long and reduced the cross-section from 608 x 608 mm to 350 x 350 mm. The length of the test section was 1000 mm, where the sample tray (176 x 325 x 40 mm) was placed centrally 2270 mm downstream of the fan (Figure 3-2). Each sample was exposed to a continuous airflow of 13.57 m/s for 120 s. Soil losses were measured 2, 7, 14 and 28 days after solution application using a Kern PES 4200-2M scale with a resolution of 0.01 g.

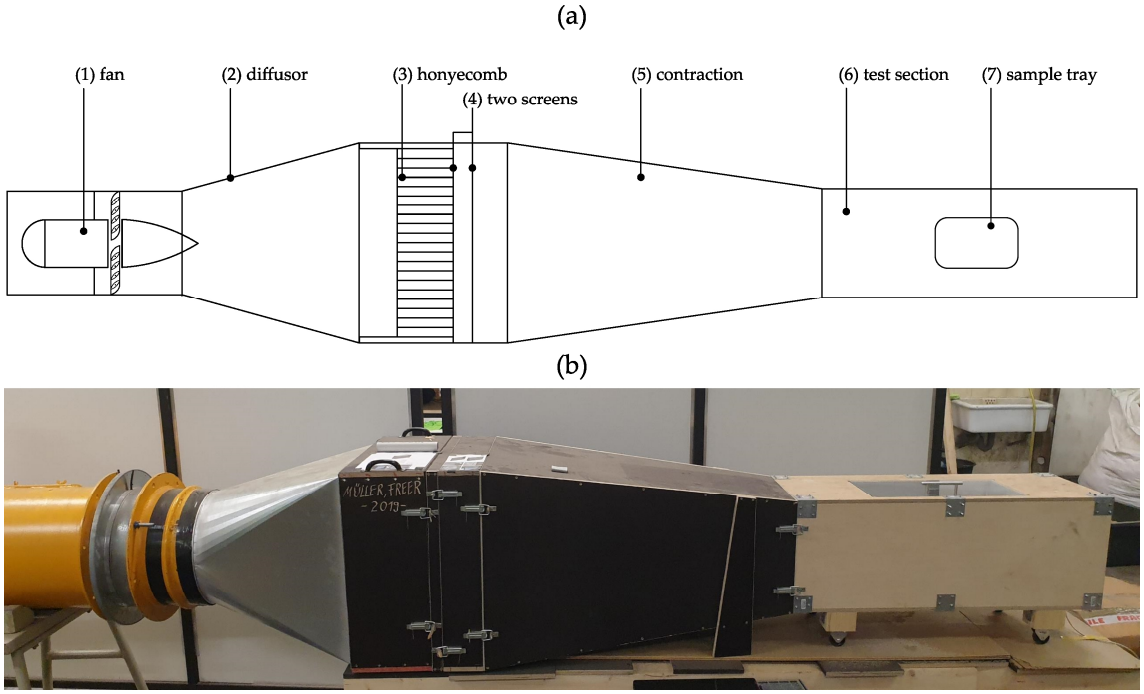


Figure 3-1. Wind tunnel used for laboratory wind erosion experiments: **(a)** schematic plan view, and **(b)** side view.

Wind erosion experiments comprised two phases. In the first phase, amendments were applied at different concentrations with a fixed application rate of 1 L/m² to identify the optimum level, whereas an increase in concentration has only insignificant effects on wind-induced soil losses. Subsequently, the impact of the application rate on the dust control effectiveness of the tested biomaterials was established. Solutions were applied at their corresponding optimum concentration as previously determined. The dust control effectiveness is defined herein as the ratio of total weight loss between treated and untreated mine soil. Arithmetic mean and standard deviation values were calculated for each configuration. A two-way ANOVA was carried out to analyze the effects of additive concentrations and application rates on wind-induced soil losses.

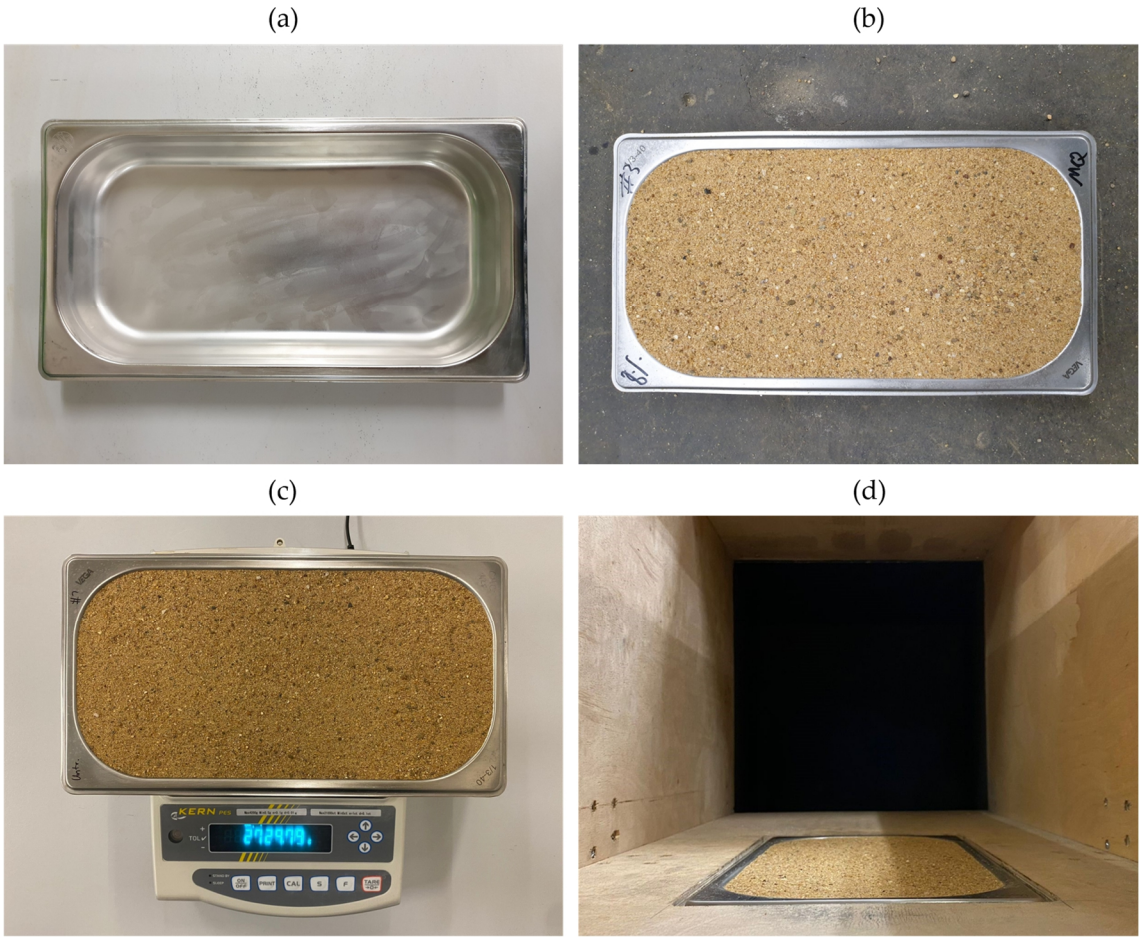


Figure 3-2. Sample preparation for the wind tunnel experiments: **(a)** sample tray, **(b)** prepared sample, **(c)** sample weighing with a Kern PES 4200-2M, and **(d)** installed sample in the wind tunnel. The dimensions of each sample tray are 176 mm x 325 mm x 40 mm.

3.3 Results

3.3.1 Effect of Additive Concentration on Wind-Induced Soil Losses

Wind-induced soil losses of specimens treated with different biomaterial solutions and additive concentrations are shown in Figure 3-3. Each data point represents the calculated mean from three replicates and indicates the total weight loss (TWL) after 28 days of soil treatment. Water-treated soil was selected as a control. As depicted in Figure 3-3, all specimens treated with biomaterials demonstrated a remarkable improvement in mass losses compared to an application with pure water. Among the tested reagents, corn steep liquor had the highest effect on the erosion behavior of treated soil surfaces. Applying 9 % of corn steep liquor decreased the TWL from 86.41 g for water-treated soil to 0.25 g. Palatinose molasses was most effective at 8 % and showed a TWL of 0.51 g. Comparable results were obtained with decantation syrup at 6 % with a TWL of 0.54 g. Chicory vinasses can be considered the least effective reagent, which achieved its lowest mass losses at 10 % with a TWL of 3.34 g. Detailed laboratory test data are given in Tables B-1 to B-7 of Appendix B.

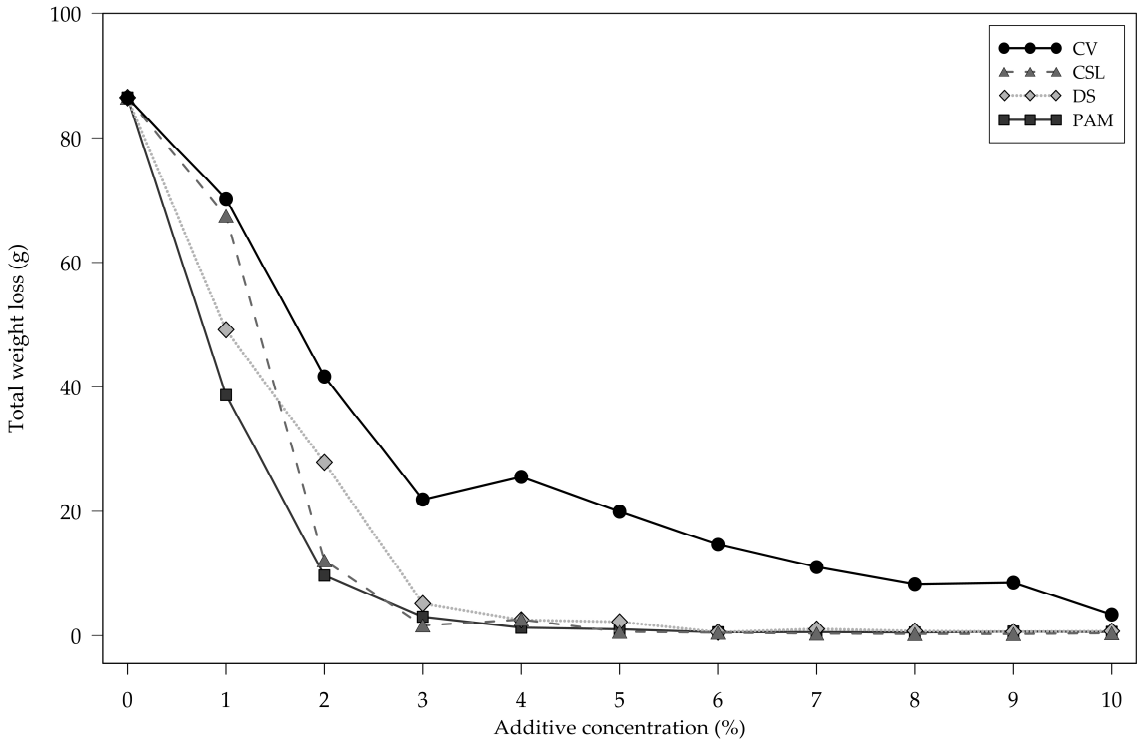


Figure 3-3. Total weight loss of sand treated with different biomaterial solutions at varying additive concentrations after 28 days of soil treatment (mean, n = 3). Biomaterials were applied with an application rate of 1 L/m². Water-treated soil is indicated with 0 %. Abbreviations: CV = Chicory Vinasses, CSL = Corn Steep Liquor, DS = Decantation Syrup, PAM = Palatinose Molasses.

Table 3-3. Results of two-way ANOVA ($\alpha = 0.05$).

Parameter	Factor	SS	df	MS	F	p
Soil loss at different additive concentrations	Reagent type	5074.432	3	1691.477	25.243	<0.001
	Concentration	31054.386	9	3450.487	51.495	<0.001
	Interaction	2771.909	27	102.663	1.532	0.074
	Error	5360.532	80	67.007		
Soil loss at different application rates	Reagent type [a]	120524.986	4	30131.246	1070.025	<0.001
	Application rate	7842.216	7	1120.317	39.785	<0.001
	Interaction	7217.818	28	257.779	9.154	<0.001
	Error	2252.751	80	28.159		

Note. Abbreviations: SS = Sum of Squares, df = Degrees of Freedom, MS = Mean Square, F = F-statistic, p = p-value.

[a] The suppressant type includes water.

It is apparent from the graph (Figure 3-3) that increasing additive concentration reduced soil losses. Data of corn steep liquor, decantation syrup and palatinose molasses follow a trend resembling an exponential decay function. Mass losses first decreased steeply and then flattened off asymptotically with increasing concentration until a plateau was reached. Applications of 3 %-solutions already significantly minimized soil losses, with corn steep liquor, decantation syrup and palatinose molasses achieving a mass loss reduction of 98.2 %, 94.1 % and 96.5 %, respectively, compared to water-treated soil. Above a concentration of 5 %, mass losses of corn steep liquor-reinforced soil stagnated, where an increase in concentration had only a marginal effect on soil sta-

bilization. Decantation syrup and palatinose molasses showed this effect from a concentration of 6 %. Soil stabilized with chicory vinasses behaved slightly differently, whereby soil losses continuously decreased with increasing concentration but did not reach a plateau. In the lower concentration range (i.e., 1-3 %), soil losses were characterized by a substantial decrease. Mass losses then diminished considerably and remained almost constant with increasing concentration. A two-way ANOVA depicted in Table 3-3 revealed that suppressant type ($p < 0.001$) and additive concentration ($p < 0.001$) did have a statistically significant effect on wind-induced soil losses.

3.3.2 Effect of Application Rate on Wind-Induced Soil Losses

Figure 3-4 plots the effects of application rate on wind-induced soil losses of biomaterial-treated sand. Each data point represents the calculated mean from triplicates and indicates the TWL after 28 days of soil treatment. Biomaterials were applied at their corresponding optimum concentration as previously determined in section 3.1. Pure water and untreated soil were selected as control group. From the graph (Figure 3-4), it can be seen that the application of solutions (i.e., water with biomaterials or pure water) at any investigated application rate reduced mass losses compared to untreated specimens, even for samples treated with only 0.25 L/m². Applications of 0.25 L/m² chicory vinasses, decantation syrup, palatinose molasses and corn steep liquor decreased the TWL from 123.04 g for untreated soil to 62.72 g, 15.69 g, 11.85 g and 1.85 g, respectively. By comparing, pure water obtained a TWL of 98.44 g. Moreover, all biomaterials achieved their minimum soil losses on a similar scale but at different application rates. Chicory vinasses had the highest effect at an application rate of 2 L/m² with a TWL of 0.79 g. Decantation syrup and corn steep liquor were most effective at an application rate of 1 L/m² with a TWL of 0.54 g and 0.47 g, respectively. Palatinose molasses showed the highest stabilization effect at 2 L/m² with a TWL of 0.37 g. Pure water can be considered as least effective among the tested solutions, which showed the lowest soil losses with a TWL of 75.41 g at an application rate of 2 L/m². Detailed laboratory test data are given in Tables B-8 to B-13 of Appendix B.

Further data analysis shows that soil losses followed a similar trend to that identified in section 3.3.1 (cf. Figure 3-3 and Figure 3-4). With increasing application rate, soil losses first decreased strongly and then flattened off asymptotically to a level where the TWL almost stagnated. This stagnation became apparent for corn steep liquor from 0.75 L/m². Above this level, an increase in application rate had only minor or no impact on improving soil erosion resistance. Decantation syrup and palatinose molasses showed this effect at 1 L/m², whereas the soil loss reduction of chicory vinasses stagnated at 1.5 L/m². Simple main effects analysis revealed that application rate ($p < 0.001$) and suppressant type ($p < 0.001$) did have a statistically significant effect on wind-induced soil losses (Table 3-3).

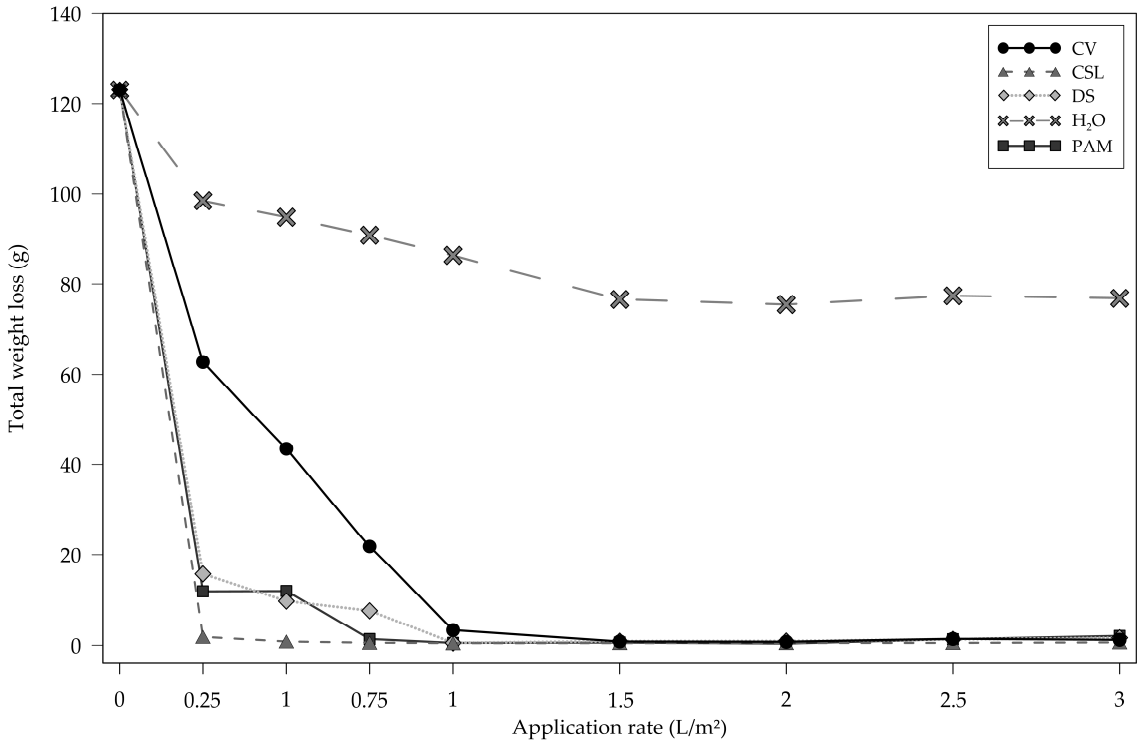


Figure 3-4. Total weight loss of sand treated with different biomaterial solutions and pure water at varying application rates after 28 days of soil treatment (mean, n = 3). Biomaterials were applied at their respective optimum concentration. Untreated soil is indicated with 0 L/m². Abbreviations: CV = Chicory Vinasses, CSL = Corn Steep Liquor, DS = Decantation Syrup, PAM = Palatinose Molasses.

3.3.3 Dust Control Effectiveness

In this study, the quantitative dust control effectiveness indicates the ratio of total weight loss between treated and untreated mine soil. Table 3-4 indicates that all investigated biomaterials achieved a similar maximum dust control effectiveness but at different application rates. Chicory vinasses was most effective at an application rate of 2 L/m² with a dust control effectiveness of 99.4 %. In comparison, chicory vinasses applied at its optimum application rate (i.e., 1.5 L/m²) decreased 99.3 % of soil losses. Decantation syrup and corn steep liquor peaked at an application rate of 1 L/m², reducing 99.6 % of soil losses. Palatinose molasses had the highest soil loss reduction at 2 L/m² with a dust control effectiveness of 99.7 %. A similar effect showed palatinose molasses applied at its optimum application rate (i.e., 1 L/m²), achieving a dust control effectiveness of 99.6 %. Pure water reached its peak at an application rate of 2 L/m² and minimized 38.7 % of soil losses.

Table 3-4. Calculated dust control effectiveness of tested biomaterial solutions and pure water after 28 days of soil treatment. Biomaterials were applied with different application rates and at their respective optimum concentration. The quantitative dust control effectiveness represents the ratio of total weight loss between treated and untreated mine soil. Effectiveness against water is given in brackets.

Substance	Application rate (L/m²)							
	0.25	0.5	0.75	1	1.5	2	2.5	3
CV	49.0 % (36.3)	64.7 % (54.2)	82.2 % (76.0)	97.3 % (96.1)	99.3 % (98.9)	99.4 % (99.0)	98.8 % (98.2)	99.0 % (98.4)
CSL	98.5 % (98.1)	99.3 % (99.1)	99.5 % (99.4)	99.6 % (99.5)	99.6 % (99.4)	99.6 % (99.3)	99.6 % (99.3)	99.5 % (99.2)
DS	87.2 % (84.1)	92.1 % (89.8)	93.8 % (91.6)	99.6 % (99.4)	99.3 % (98.8)	99.2 % (98.8)	98.9 % (98.3)	98.7 % (97.9)
PAM	90.4 % (88.0)	90.3 % (87.4)	98.9 % (98.5)	99.6 % (99.4)	99.5 % (99.2)	99.7 % (99.5)	98.9 % (98.3)	98.3 % (97.3)
H_2O	20.0 %	22.9 %	26.1 %	29.8 %	37.8 %	38.7 %	37.2 %	37.6 %

Note. Substances were applied at the following concentrations: CV (10 %), CSL (5 %), DS (6 %), and PAM (6 %). Abbreviations: CV = Chicory Vinasses, CSL = Corn Steep Liquor, DS = Decantation Syrup, PAM = Palatinose Molasses.

3.4 Discussion

3.4.1 Possible Mechanisms of Dust Suppression

The present study shows that by-products from the food industry effectively reduce wind-induced soil losses, indicating an improved erosion behavior of soils (Table 3-4). There are generally two mechanisms of how dust suppressants can enhance the erodibility of soils and thus prevent soil particles from becoming airborne, namely hygroscopicity and agglomeration (Parvej et al. 2021). Hygroscopicity refers to the property of substances to absorb moisture from the environment (Wrolstad 2012). Such reagents increase the moisture content of soils, which directly contributes to soil cohesion (Chen et al. 1996). That enhancement in inter-particle bonding can be attributed to capillary forces and absorbed water films on the surface of the soil particles (Fécan et al. 1999). In comparison, dust suppression by agglomeration causes a consolidated accumulation of previously loose soil particles. These dust suppressants establish and reinforce bonds between soil particles due to adhesive and cohesion forces, solidifying as the solution sets. Thus, agglomerated particles form a protective layer that protects unconsolidated loose soil grains below the surface from erosive forces (Parvej et al. 2021).

Observed biomaterials' effectiveness can probably be attributed to the agglomeration of soil particles. Freer et al. (2022a) showed that these biomaterials could significantly increase the mechanical strength of soils, indicating a reinforcement in inter-particle bonding. Consequently, the biomaterials can agglomerate soil particles and thus create a soil surface where aerodynamic drag and lift forces generated in the wind tunnel are insufficient to induce wind erosion. Dust suppression by absorbing moisture from the environment would also be possible because they consist of low-molecular carbohydrates, which can be highly hygroscopic in an amorphous state (Wrolstad 2012). However, treated specimen surfaces did not appear to be moist after conducting the experiments but rather exhibited characteristics of a crust.

3.4.2 Effect of Additive Concentration on Wind-Induced Soil Losses

The ANOVA results (Table 3-3) reveal that both additive concentration ($p < 0.001$) and dust suppressant type ($p < 0.001$) have significant effects on the wind erosion resistance of the soil. As shown in Figure 3-3, soil losses generally decrease with increasing biomaterial concentration, indicating improved dust control effectiveness. Observed stagnations in soils losses (Figure 3-3, Tables B-1 to B-7 of Appendix B) suggests an optimum concentration for corn steep liquor, decantation syrup and palatinose molasses, around at 5 %, 6 % and 6 %. These concentrations were selected because an increase above these levels showed negligible effects on biomaterials' performance. Similar data trends were reported by Omane et al. (2017) and Cybulski et al. (2015), who studied the dust control performance of different reagents (e.g., molasses, polymers, surfactants) at varying concentrations. They concluded that each dust suppressant probably has its optimum concentration that can be used to manage the trade-off between effectiveness and cost-efficiency (Cybulski et al. 2015; Omane et al. 2017). Chicory vinasses appears to have an optimum concentration above 10 %, as soil losses have not reached a plateau (Figure 3-3, Tables B-1 to B-7 of Appendix B).

3.4.3 Effect of Application Rate on Wind-Induced Soil Losses

Based on the ANOVA results (Table 3-3), it can be concluded that application rate ($p < 0.001$) and dust suppressant type ($p < 0.001$) have significant effects on wind-induced soil losses. Figure 3-4 demonstrates that soil losses generally decrease with increasing application rate, implying enhanced dust control performance. These findings concur with Owji et al. (2021), who showed that increasing application rates of guar gum and carboxymethyl cellulose solutions from 1 L/m² to 2 L/m² significantly improved wind erosion resistance. Lemboye et al. (2021) also reported that raising the application rate enhances the effectiveness of biopolymers in preventing a wind-induced soil losses. Observed stagnation in soils losses (Figure 3-4, Tables B-8 to B-13 of Appendix B) indicates an optimum application rate for corn steep liquor, chicory vinasses, decantation syrup, and palatinose molasses, probably around 0.75 L/m², 1.5 L/m², 1 L/m² and 1 L/m², respectively. These application rates were chosen, because an increase above these values yielded only minor improvements in biomaterials' effectiveness.

3.4.4 Comparison of Additive Concentration, Application Rate and Effectiveness of Biopolymers

Various biopolymers have been investigated in wind tunnel experiments to improve the erodibility of soils (Table 3-5). Comparing the study results with those from other works reveals that food processing by-products can achieve similar effectiveness as biopolymers (Table 3-4). As demonstrated, each biomaterial tested achieved a dust control effectiveness of > 99 %. However, a comparison of studies suggests that the amendments probably need to be applied at higher dosages per unit surface area to achieve a similar level of erosion control. For example, Lemboye et al. (2021) investigated three polysaccharides, Arabic gum, sodium alginate and pectin, to control sand erosion (Lemboye et al. 2021). Lemboye et al. (2021) ascertained that solutions of 5 % Arabic gum and 0.5 % pectin at an application rate of 1.3 L/m² were sufficient to reduce soil losses by > 99 %. Applications of 0.5 % sodium alginate resulted in a soil loss reduction of > 98 % (Lemboye et al. 2021). Owji et al. (2021) demonstrated similar carboxymethyl cellulose and guar gum performances. Their wind tunnel experiments indicated effectiveness in mitigating soil losses of > 99 % and > 97 %, respectively, for solutions of 0.7 % carbox-

ymethyl cellulose and 0.7 % guar gum applied with an application rate of 2 L/m² (Owji et al. 2021). Also, Kavazanjian et al. (2009) studied polysaccharides for wind erosion control. Kavazanjian et al. (2009) showed that applying 0.5 g/L xanthan gum and 1 g/L chitosan solutions with an application rate of 0.4 L/m² and 0.5 L/m², respectively, can decrease soil losses by > 99 %. However, it should be noted that a direct comparison of the study results with other studies investigating biopolymers is only possible to a limited extent due to differences in experimental designs. For example, the chosen wind speed in wind tunnels significantly affects the erosion rate of soils. Almajed et al. (2020) demonstrated that soil losses successively increase with increasing wind speed. There is also a specific threshold wind speed for treated and untreated soils, above which erosion rates increase considerably (Owji et al. 2021). Other parameters that may restrict a result comparison are exposure time, curing time, sampling frequency or measurement period.

Biopolymers' high effectiveness at lower dosages per unit surface area can probably be attributed to creating three-dimensional network structures by linking polymer chains and forming a surface coating on soil particles (Owji et al. 2021; Chang et al. 2015c; Chen et al. 2016). These cross-linking meshes increase inter-particle cohesive forces and thus enhance the soil's mechanical behavior. In addition, biopolymer coatings increment the mass of soil particles resting on the surface, increasing gravitational force (Ayeldeen et al. 2017).

Table 3-5. Published wind erosion test results for soils treated with biopolymers.

Biopolymer	Effectiveness (%)	Concentration	Application rate (L/m²)	Wind speed (m/s)	Soil type	Reference
Arabic gum	99.1	5.0 %	1.3	16.2	SP	Lemboye et al. (2021)
Carboxymethyl cellulose	99.0	0.7 %	2.0	14.8	SP	Owji et al. (2021)
Chitosan	99.5	1.0 g/L	0.5	7.2	SM	Kavazanjian et al. (2009)
Guar gum	97.9	0.7 %	2.0	14.8	SP	Owji et al. (2021)
Pectin	99.9	0.5 %	1.3	16.2	SP	Lemboye et al. (2021)
Sodium alginate	98.8	0.5 %	1.3	16.2	SP	Lemboye et al. (2021)
Xanthan gum	99.9	0.5 g/L	0.4	7.2	SM	Kavazanjian et al. (2009)

Note. The effectiveness was calculated as a ratio of the erosion rate between the treated and untreated soil. The soil type was classified according to the Unified Soil Classification System. Abbreviations: SP = Poorly graded sand, SM = Poorly graded non-plastic silty sand.

3.4.5 Factors Influencing the Performance of Dust Suppressants

The combined action of abiotic (e.g., temperature, radiation, water) and biotic factors (e.g., bacteria) affect the effectiveness and durability of dust suppressants. These environmental factors cause weathering of the soil surface, which impairs inter-particle bonding and thus reduce resistance to erosive forces (Piechota et al. 2004; Preston et al. 2020). Physical weathering can also diminish treatments, e.g. wildlife activity or impact force of saltating soil particles (Chen 2014).

Frequent and heavy rainfall is likely to be the dominant factor influencing biomaterials' dust control performance, as they are water-soluble and thus can be leached from soil surfaces. Bolander and Yamada (1999) reported that the effectiveness of ligninsulfonates, one of the widely applied non-traditional dust suppressants, can be considerably impaired by heavy rain due to their high sensitivity to water. Similar applies to biopolymers. Ayeldeen et al. (2017) and Toufigh and Ghassemi (2020) investigated the durability of cold water dissolving biopolymers exposed to different wet and dry cycles. Their wind tunnel experiments showed that biopolymers' effectiveness successively decreased with increasing wet and dry cycles, and erosion rates varied depending on biopolymer type and concentration (Ayeldeen et al. 2017; Toufigh and Ghassemi 2020). In this context, thermogelating biopolymers, such as agar gum or gellan gum, pose a durability benefit against rainfall and subsequent leaching because they only dissolve entirely in water at around 85-90 °C (Chang et al. 2016b; Huang et al. 2007). Chang et al. (2016b) reported that biopolymers with thermo-gelation properties maintain high strength even when exposed to water. Such a high strength can be attributed to forming a gel when heated biopolymer solution cools to ambient temperature (Chang et al. 2016b; Chang et al. 2017; Huang et al. 2007). That implies, however, that their preparation and application require specific expertise, and application equipment already available in mining operations (e.g., water truck with spray bars) cannot be used or must be modified. Equipment modifications may include agitator and heating systems.

Biodegradability is also expected to affect the dust control performance of chosen biomaterials, although this influence is considered inferior to leaching by rainfall. Prolonged exposure to environmental factors can degrade carbohydrates and proteins. For example, UV radiation initiates photo-oxidation of biopolymers, resulting in bond cleavage and molecular weight reduction (Göpferich 1996; Chamas et al. 2020). Kavazanjian et al. (2009) demonstrated that wind erosion rates of xanthan gum-treated specimens increased when exposed to sunlight. Chemical degradation via hydrolysis is also possible, where biopolymer chains react with water molecules and break up into smaller segments (Chamas et al. 2020). Moreover, microorganisms and their enzymes accelerate biomaterials' degradation. Microorganisms identify carbohydrates and proteins as food sources and cleave them by intracellular and extracellular enzymes into low-molecular-weight oligomers, dimers, and monomers, which are eventually mineralized to carbon dioxide and water (Nair et al. 2017).

3.4.6 Evaluating the Application Potential of Dust Suppressants at Mine and Mineral Processing Sites

Wind tunnel experiments are a widely applied method to evaluate the performance of dust suppressants. Here, lower soil losses indicate an improved wind erosion resistance, and thus an enhanced dust control effectiveness (Xu et al. 2018). Study results reveal that each biomaterial can significantly reduce the erosion rate of soils and achieve similar effectiveness as biopolymers (> 99 %), which has been extensively investigated in previous studies for soil stabilization and erosion control (Table 3-5). Hence, it can be concluded that food processing by-products can probably be applied effectively as dust suppressants intended for applications on exposed mine soils (e.g., tailings beaches, waste rock dumps, stockpiles or benches). However, tested biomaterials are expected to be more suitable for short-term rather than long-term dust control measures due to their susceptibility to leaching by heavy rainfall and biodegradability. Food processing by-

products might also be interesting for re-vegetation activities of closed mine sites. Besides stabilizing soil and seeds against wind erosion, biomaterials' carbohydrates and proteins could supply nutrients to plants and promote their growth (Chang et al. 2015d).

An advantage is that the biomaterials solutions are easy to prepare and can probably be applied with equipment available in mining operations, such as water trucks with spray bars. By contrast, biopolymers partly require modified or newly developed equipment due to their rheological characteristics (Chang et al. 2020). The biomaterials can either be applied topically or incorporated into the first layer of the substrate (Piechota et al. 2004). However, topical applications are expected to be more cost-effective. Although mixing reagents into substrates prolongs the treatment's service life, this durability benefit is unlikely to be realized due to biomaterials' water sensitivity and biodegradability.

Promising is also that food processing by-products are mostly low-priced, readily available, and produced in large quantities (Jõgi and Bhat 2020; Anal 2017; Mahro et al. 2015). However, low product prices do not necessarily imply cost-effective dust control. Thompson and Visser (2003) stated that equipment operating costs could often inflate the total cost of dust control. Decisive factors to be considered are reagents' durability and re-application intervals needed to maintain adequate dust suppression (Thompson and Visser 2007). Accordingly, biogenic reagents with poor water solubility, such as thermogelating biopolymers, are expected to prolong the intervals between required re-applications and thus possibly offer a cost advantage for long-term dust control practices compared to tested biomaterials.

Only minor toxic effects are expected when using food processing by-products for dust and erosion control because they can be naturally decomposed (Piechota et al. 2004). Nevertheless, their application to mine soils might have some shortcomings. Considering their water-solubility, tested biomaterials could increase the biological oxygen demand in freshwater ecosystems due to mobilization in rainfall-runoff, impairing aquatic organisms (Steevens et al. 2007; Li et al. 2021). Also possible would be odour emissions, mold growth on treated surfaces or nuisance caused by attracted insects and wildlife (Jones 2017; Edvardsson et al. 2012).

3.4.7 Limitations of the Study

Study results indicate that tested by-products from the food industry can be applied as dust suppressants intended for applications on exposed mine soils. Nonetheless, the findings of this study have to be seen in light of some limitations. (1) No field trials were performed to verify the laboratory results. Environmental factors such as UV light or rainfall and microbial degradation likely affect biomaterials' performance and durability. (2) Wind erosion tests were conducted with a fixed wind speed. Any modification in wind speed could change the soil losses and thus lead to different evaluations of the biomaterials' effectiveness in suppressing dust emissions. (3) Specimens were not compacted. The resulting loose substrate surfaces could potentially lead to errors in data collection. (4) Study results' significance is limited concerning biomaterials' applicability as dust suppressants on unpaved roads because applied laboratory experiments only simulated wind erosion and not the abrasive forces from vehicles, which considerably affect dust generation (Katra 2019). (5) Wind erosion tests conducted on soils with different grain size distributions may show different results because soil type can affect

strength improvements induced by additives and thus the effectiveness of dust suppression (Tingle and Santoni 2003; Xu et al. 2018).

3.5 Conclusions

The present study examined the effectiveness of four biodegradable food processing by-products as dust suppressants. The following conclusions can be drawn from the results:

- Carbohydrate- and protein-rich biomaterials can significantly reduce wind-induced soil losses, indicating applications as dust suppressants.
- Each biomaterial tested achieved a dust control effectiveness of > 99 %, but at different concentrations and application rates. The application of pure water reduced wind-induced soil losses to less than 39 %.
- There are optimum concentrations and optimum application rates for each biomaterial. Higher concentrations, respectively, application rates showed a negligible or no impact on biomaterials' dust control effectiveness.

Hence, these findings provide solid empirical confirmation that food processing by-products can be applied as dust suppressants on exposed mine soils. However, future research is required on how environmental factors (e.g., rainfall, solar radiation) influence the effectiveness of such surface treatments in suppressing dust emissions.

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Chapter 4
Influence of Environmental Conditions on the Effectiveness of Dust Suppressants

A version of this chapter has been published in the journal of Applied Sciences entitled "Effectiveness of food processing by-products as dust suppressants for exposed mine soils: results from laboratory experiments and field trials".

Published	14 November 2022
Authors	Justus Freer, Maximilian Lübeck, Johannes L. Sieger, Bernd G. Lottermoser, and Marius Braun
Citation	Freer, J.; Lübeck, M.; Sieger, J. L.; Lottermoser, B. G.; Braun, M. (2022): 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). DOI: 10.3390/app122211551.

4.1 Introduction

Dust suppressants effectively mitigate particulate matter emissions from exposed mine soils by changing the physical properties of soil surfaces (Piechota et al. 2004). Their effectiveness and durability are decisively impacted by environmental factors such as precipitation, radiation or the presence of microorganisms. For example, heavy rainfall can significantly impair the performance of ligninsulfonates, which are widely applied as non-traditional dust suppressants, due to their water solubility (Bolander and Yamada 1999). Exposure to ultraviolet radiation causes photo-oxidation of polymer-based reagents, where polymer chains cleavage into smaller segments, resulting in deterioration of the mechanical properties (Yousif and Haddad 2013). Biogenic amendments (e.g., biopolymers or molasses), in turn, can be naturally decomposed by microorganisms. Carbohydrates and proteins are recognized as food sources and split into oligomers, dimers, and monomers by microorganisms' intra- and extracellular enzymes (Nair et al. 2017). Hence, field trials are imperative to evaluate the actual performance of dust suppressants and to enable an appropriate product selection for applications at mine and mineral processing sites. A variety of field studies (e.g., Monlux and Mitchell 2007; Gillies et al. 1999; Edvardsson et al. 2012) have examined the effectiveness of dust suppressants on heavily trafficked surfaces such as unpaved roads. However, there is a lack of experimental research investigating the effects of amendments on reducing wind-blown dust emissions from exposed mine soils under field conditions (Katra 2019).

Currently applied and investigated dust suppressants (e.g., electrochemical products, magnesium chloride, ligninsulfonates, biopolymers) have limitations and disadvantages, such as high product prices, may be detrimental to the environment, are insoluble in cold water, or yield viscous solutions at low concentrations (Kunz et al. 2022; Hataf et al. 2018; Mudgil et al. 2014; Chang et al. 2016a). Food processing wastes and by-products may pose sustainable alternatives to established dust suppressants. They are usually inexpensive, readily available and generated in high volumes (Jõgi and Bhat 2020; Anal 2017; Mahro et al. 2015). Moreover, many of these materials are biodegradable and contain carbohydrates and proteins, which provide techno-functional properties to bind single soil particles (Anal 2017). A study has recently shown that wastes and by-products from the food industry can enhance the unconfined compressive strength of soils, which indicates an improved wind erosion resistance and thus an enhanced dust control effectiveness (Freer et al. 2022a). Freer et al. (2022a) concluded that among the biomaterials studied, chicory vinasses, corn steep liquor, decantation syrup, and palatinose molasses have the highest potential to be applied as dust suppressants. In a follow-up study, Freer et al. (2022b) conducted laboratory-based wind tunnel tests and demonstrated that these biomaterials could indeed effectively mitigate wind-induced soil losses. Even though these results are promising for the actual application of wastes and by-products from the food industry as dust suppressants on mine soils, the study did not consider abiotic (e.g., radiation, water) and biotic factors (e.g., bacteria), which may diminish the effectiveness of reagents to reduce dust emissions (Gillies et al. 1999). Rainfall, in particular, may be a controlling factor on amendments' effectiveness because water-soluble reagents can be leached from the surfaces of treated soils and substrates.

This study aimed to evaluate the effectiveness of four biodegradable by-products from the food industry (chicory vinasses, corn steep liquor, decantation syrup, and

palatinose molasses) in reducing dust emissions from mine soils. The effectiveness of dust suppression from soils is defined herein as the degree to which by-products from the food industry successfully reduce wind erosion from a selected sandy mine soil as measured with and without dust control. Laboratory experiments were performed to study the effects of rainfall intensities and wetting-drying cycles on the wind erosion resistance of treated soil surfaces. In addition, field trials were conducted to establish the effectiveness of applied biomaterials under actual field conditions that are indicative of possible commercial-scale application and practice. For this study, a low-cost and low-maintenance experimental setup was applied that is feasible for remote and difficult-to-access areas and allows various dust control products to be tested. Thus, this research extends our knowledge of the application of biodegradable dust suppressants on mine soils and supports the implementation of sustainable dust control measures at mine and mineral processing sites.

4.2 Materials and Methods

4.2.1 Mine Soil

Test substrate used in this study was sampled from a sand and gravel pit in North-Rhine Westphalia, Germany. According to (DIN EN ISO 14688-1:2018-05), the mine soil can be classified as medium-coarse sand (D_{50} = 0.65 mm). X-ray diffraction analysis indicated that the sand is dominated by quartz, with minor amounts of orthoclase, microcline and clinochlore. Detailed material characterization of the test substrate can be found in Freer et al. (2022a).

4.2.2 By-Products from the Food Industry

Four by-products from the food industry were investigated as dust suppressants. Each reagent is biodegradable and readily soluble in water. Further information on tested biomaterials can be taken from Freer et al. (2022b).

4.2.2.1 Chicory vinasses

Chicory vinasses is a viscous liquid obtained as a by-product during inulin and oligofructose production from chicory. Its dry matter (DM) content is 63.3 %, crude protein being the main component (45–51 % in DM). Samples of chicory vinasses were acquired from BENEO-Orafti S.A. (Freer et al. 2022a).

4.2.2.2 Corn steep liquor

Corn steep liquor is a by-product of the steeping process of corn and has a DM content of 27.0 %. DM components are crude protein (36–49 % in DM), starch, reducing sugars and crude fiber. Cargill Deutschland GmbH supplied samples of corn steep liquor (Freer et al. 2022a).

4.2.2.3 Decantation syrup

Decantation syrup is obtained as a viscous liquid during the production of candy sugar and has a DM content of 72.0 %. Its DM consists mainly of sucrose, besides small amounts of fructose, glucose, and oligosaccharides. BENEO-Orafti S.A. provided samples of decanter syrup (Freer et al. 2022a).

4.2.2.4 Palatinose molasses

Palatinose molasses is the concentrated liquid fraction from the isomaltulose production from sugar beets and has a DM content of 68.2 %. DM components are isomal-

tulose and trehalulose (> 50 % in DM) and sucrose, isomaltose, fructose and glucose (28–42 % in DM). Samples of palatinose molasses were acquired from BENEO-Orafti S.A. (Freer et al. 2022a).

4.2.3 Laboratory experiments

4.2.3.1 Materials

Selected biomaterials were dissolved in pure water to their specific concentration using a magnetic stirrer to prepare homogeneous solutions (Figure 4-1). Chosen reagent concentrations are shown in Table 4-1. It should be noted that the reagent concentration is referred to as the dry matter content of the additive. The specific concentration of each additive and its application rate were selected based on Freer et al. (2022b) who have identified the optimum parameters, whereby a further increase in concentration and application rate has an insignificant effect on the biomaterial's effectiveness to reduce dust emissions.

Three soil replicates were prepared for each wind erosion test to evaluate the precision of measured soil losses, while dry, untreated soil was selected as control samples to determine applied biomaterials' quantitative dust control effectiveness. The prepared solutions were then sprayed on soil surfaces according to their specific application rate (Table 4-1). In order to ensure consistent solution application covering entire soil surfaces and to prevent any disturbance of soil surfaces, the solutions were carefully applied with a hand-held trigger sprayer. As other studies have stated (e.g., Si and Herrera (2007)), an effective performance of dust suppressants requires careful and uniform product application. Prior to wind tunnel experimentation, prepared soils were air-dried for seven days at ambient laboratory temperature.

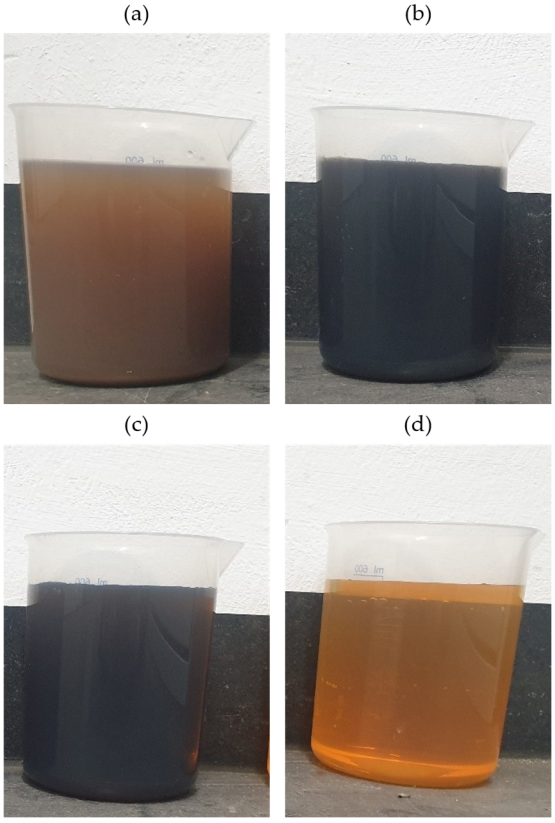


Figure 4-1. Prepared biomaterial solutions: **(a)** chicory vinasses, **(b)** corn steep liquor, **(c)** decantation syrup, and **(d)** palatinose molasses.

Table 4-1. Applied additive concentration and application rate of each biomaterial.

Substance	Concentration (%)	Application rate (L/m²)
Chicory vinasses	10.0	1.5
Corn steep liquor	5.0	0.75
Decantation syrup	6.0	1.0
Palatinose molasses	6.0	1.0

Note. The concentration and application rate of each reagent were determined based on the findings of Freer et al. (2022b), who identified the optimum parameters that result in maximum effectiveness in reducing dust emissions. Further increases in concentration and application rate were found to have little impact on the performance of the biomaterial.

4.2.3.2 Experimental Methodology

Wind erosion tests were performed using a laboratory wind tunnel of the Institute of Mineral Resources Engineering, RWTH Aachen University, Germany (Figure 3-1). This facility has already been used for evaluating the effectiveness of biogenic dust suppressants (Freer et al. 2022b). Sample trays were placed centrally in the test section and exposed to a laminar airflow of 13.57 m/s for 120 s.

In subsequent laboratory experiments, treated soil surfaces were investigated whether different rainfall intensities and repetitive wetting-drying cycles impact the dust control effectiveness of the investigated biomaterials. Four different rainfall intensities were tested: (a) 0.25 L/m², (b) 1 L/m², (c) 2 L/m², and (d) 4 L/m². For this, pure water was applied on the soil surfaces using a hand-held trigger sprayer. The first application of water was carried out seven days after applying biomaterials. Then, individual samples were moistened with their chosen rainfall intensities (wet-dry cycle 1) and stored in a room at ambient temperature. After seven days of drying, the specimens were tested again in the wind tunnel and then wetted once again (wet-dry cycle 2). The same procedure was used for the following three wet-dry cycles (3–5). The sample tray was weighed before and after each measurement using a Kern PES 4200-2M with a resolution of 0.01 g. Untreated mine soil was selected as a control to calculate the dust control effectiveness for each experimental setup. Quantitative dust control effectiveness is therefore defined as the ratio of total weight loss between treated and untreated mine soil after four wet-dry cycles. Statistical analysis of measured soil losses included calculating arithmetic mean and standard deviation values.

4.2.4 Field Trials

4.2.4.1 Test Site and Materials

A field test site was established at an open-pit lignite mine in North Rhine-Westphalia, Germany (Figure 4-2c), where field experimentations were conducted between July and August 2020. Initially, the test site was cleared of vegetation and topsoil. Then, 18 test plots were constructed using wooden frames (length 700 mm, width 400 mm, height 56 mm) and geotextile fabric, which was attached to the bottom surface of each frame to separate the test substrate from the underlying soil and to allow for water drainage (Figure 4-2a). Then, each test plot was filled with mine soil up to the top of each wooden frame. Each soil surface was then levelled, and finally, soil surfaces were treated with selected additives (Figure 4-3). Reagent solutions' preparation and application on the substrate surface were identical to the procedure described in 2.3.1. Untreated mine

soil and soil only treated with water were set up as a control group to establish the dust control effectiveness of selected biomaterials.



Figure 4-2. Images of field test site: **(a)** construction design of individual test plot showing wooden frame and geotextile base, **(b)** experimental setup of a single test plot with electric blower, isokinetic sampling probe and dust monitor DustTrak DRX 8533, and **(c)** entire test site with installed soil plots and nearby weather station.

Three measurement series were carried out on each sampling day to determine the average background particulate matter concentration at the test site (cf. Tables C-9 to C-11, Appendix C). Meteorological data were obtained from a nearby weather station for the duration of the study (12:00, 17 July 2020–12:00, 14 August 2020). Daily mean data included temperature (°C), solar radiation (W/m²), humidity (%) and precipitation (L/m²). A summary of the recorded meteorological data is given in Table 4-2. The lowest daily mean temperature for the study period was 16.04 °C, with the highest daily mean temperature of 28.04 °C. In total, a precipitation amount of 39.44 L/m² was measured. The highest rainfalls were recorded at 9, 23, 26 and 27 days after soil treatment with 4.8 L/m², 4.25 L/m², 17.48 L/m², and 8.84 L/m², respectively.

Table 4-2. Meteorological data for the study site and study period.

Days post-application	Date	Temperature (°C)			Humidity (%)	Global radiation (W/m²)	Precipitation (L/m²)
		MIN	MAX	M			
0	17.07.20	18.61	21.84	20.10	68.48	217.51	0.01
1	18.07.20	12.90	27.56	21.21	65.89	292.44	0.29
2	19.07.20	15.21	28.30	22.24	59.82	278.16	0.08
3	20.07.20	14.33	22.48	17.78	68.82	135.69	0.00
4	21.07.20	10.04	21.78	16.04	62.25	306.56	0.05
5	22.07.20	9.80	22.06	16.37	62.31	293.56	0.00
6	23.07.20	9.35	25.89	18.69	56.23	310.89	0.18
7	24.07.20	17.29	24.84	20.46	58.70	202.74	0.02
8	25.07.20	14.94	25.30	21.05	64.87	109.04	0.21
9	26.07.20	16.04	23.25	19.53	72.65	220.62	4.80
10	27.07.20	12.87	30.25	21.40	58.40	175.06	0.74
11	28.07.20	16.46	23.63	20.45	57.46	222.27	0.01
12	29.07.20	13.19	23.39	18.29	59.13	267.38	0.04
13	30.07.20	10.60	28.22	20.07	55.16	298.25	0.04
14	31.07.20	15.15	35.56	25.78	42.94	309.94	0.06
15	01.08.20	21.46	30.95	25.43	55.01	205.48	0.67
16	02.08.20	16.92	23.92	20.33	63.76	191.84	0.01
17	03.08.20	10.99	23.27	17.73	61.83	202.76	0.09
18	04.08.20	12.98	23.33	17.79	60.71	279.16	0.02
19	05.08.20	12.39	30.37	21.79	44.47	300.26	0.03
20	06.08.20	17.17	31.67	24.82	39.82	290.72	0.02
21	07.08.20	16.91	33.98	26.52	41.35	293.58	0.07
22	08.08.20	17.54	35.84	28.04	42.61	282.54	0.03
23	09.08.20	21.27	33.20	25.08	58.56	114.01	4.25
24	10.08.20	19.09	33.44	26.74	58.13	242.12	0.02
25	11.08.20	21.63	34.42	26.65	57.93	179.42	1.38
26	12.08.20	19.86	31.68	23.68	75.36	182.34	17.48
27	13.08.20	20.05	31.98	24.84	71.71	196.22	8.84
28	14.08.20	18.62	25.79	21.84	74.67	96.42	0.00

Note. Meteorological data were obtained from a nearby weather station for the duration of the field study (i.e., 12:00, 17 July 2020–12:00, 14 August 2020). Abbreviations: M = Mean, MAX = Maximum, MIN = Minimum.

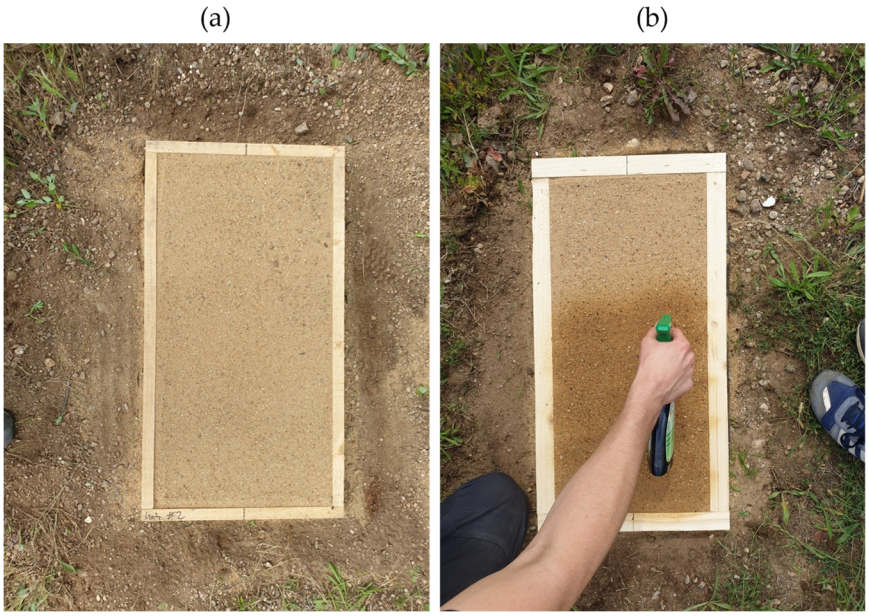


Figure 4-3. Sample preparation for the field experimentation: **(a)** leveled soil plot filled with mine soil, and **(b)** reagent application with a hand-held trigger sprayer onto the test plot.

4.2.4.2 Experimental Methodology

To simulate wind erosion events, a commercially available electric blower was repetitively applied to each treated soil plot surface, and dust measurements were carried out at particular times over a period of 28 days. At each test plot, suspended dust concentrations were measured 3, 7, 14, 21 and 28 days after substrate treatment, whereby $PM_{2.5}$, PM_{10} and total suspended particle (TSP) concentrations were determined in the air (i.e., mg per m^3), using a DustTrak DRX 8533 from TSI with a log interval of 1 s (Figure 4-4a). The DustTrak DRX 8533 records aerosol concentrations in a range of 0.001–150 mg/m^3 (± 0.1 % of reading). Isokinetic sampling was applied to avoid biased measurements of particulate concentration, using a 90-degree bent tubing with a streamlined inlet (Figure 4-4b). A 2 mm inlet diameter was selected to match the probe inlet velocity to the generated airflow velocity. The isokinetic probe was placed centrally opposite the applied wind direction at the height of 450 mm above the wooden frame (Figure 4-2b).

The duration of each measurement was 60 s, whereby the test plot surface was subjected to a continuous airstream from the electric blower for 45 s, which generated a constant wind speed of 14.65 m/s (i.e., 52 km/h). The wind speed was measured using an anemometer positioned at the test plot end. However, it should be noted that such blowers generate a turbulent flow and do not meet the aerodynamic criteria of portable field wind tunnels, simulating the atmospheric flow causing natural wind erosion (van Pelt and Zobeck 2013). Consequently, the measured dust emissions do not equate to dust emissions caused by natural wind erosion. Measured particulate matter concentrations were initially analyzed for the presence of outliers and extreme values using box-plot graphics. Implausible or illogical values (e.g., negative values) were removed from the data set before the mean concentration of TSP, PM_{10} and $PM_{2.5}$ were calculated. In addition, photographic images were taken before and after each measurement to document changes in the soil plot surfaces.

(a) (b)

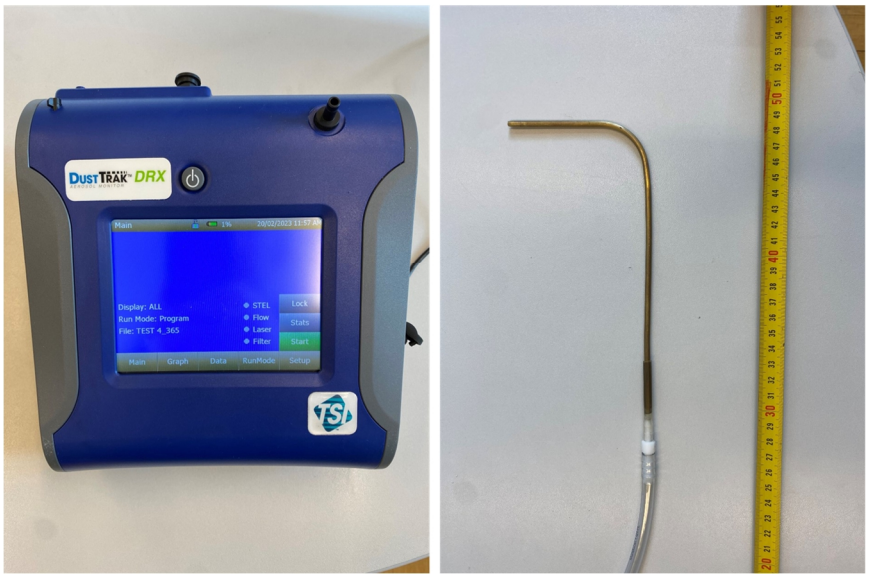


Figure 4-4. Measuring equipment for the field experiments: **(a)** dust monitor DustTrak DRX 8533, and **(b)** isokinetic sampling probe.

4.3 Results

4.3.1 Laboratory Testing

4.3.1.1 Effect of Rainfall Intensities on Wind-Induced Soil Losses

Wind-induced soil losses of samples treated with different biomaterial solutions and wetted with four varying rainfall intensities are shown in Figure 4-5. Each bar represents the calculated mean from triplicates and indicates the total weight loss (TWL) after four wet-dry cycles. Prior to the first wet-dry cycle, soil treated with chicory vinasses, corn steep liquor, decantation syrup and palatinose molasses showed only negligible weight losses of 0.09 g *(SD = 0.02)*, 0.12 g (*SD = 0.16*), 0.04 g (*SD = 0.01*), and 0.03 g (*SD = 0.01*), respectively. From Figure 4-5, it can be seen that wetting of samples increased mass losses at any investigated rainfall intensity. Samples treated with chicory vinasses can be considered the most susceptible to wind erosion, showing the highest mass losses at a rainfall intensity of 0.25 L/m² with a TWL of 63.04 g. Samples treated with corn steep liquor, decantation syrup and palatinose molasses were less prone to wetting and peaked in mass losses at a rainfall intensity of 0.25 L/m² with a TWL of 4.38 g, 2.79 g, and 13.52 g, respectively. By comparison, untreated soil has a TWL of 125.28 g (*SD = 19.34*) after four measuring cycles.

Mass losses of each biomaterial-treated soil wetted with higher rainfall intensities (1–4 L/m²) were significantly lower than those moistened with only 0.25 L/m². With increasing rainfall intensity, the TWL of soil treated with chicory vinasses decreased to 5.35 g (1 L/m²), 0.6 g (2 L/m²) and 2.12 g (4 L/m²), respectively. Corn steep liquor behaved similarly and showed a reduced TWL of 1.24 g (1 L/m²), 0.7 g (2 L/m²) and 2.38 g (4 L/m²). By contrast, all soil samples treated with decantation syrup and palatinose molasses had a TWL of < 1 g. Detailed laboratory test data are given in Tables C-1 to C-8 of Appendix C.

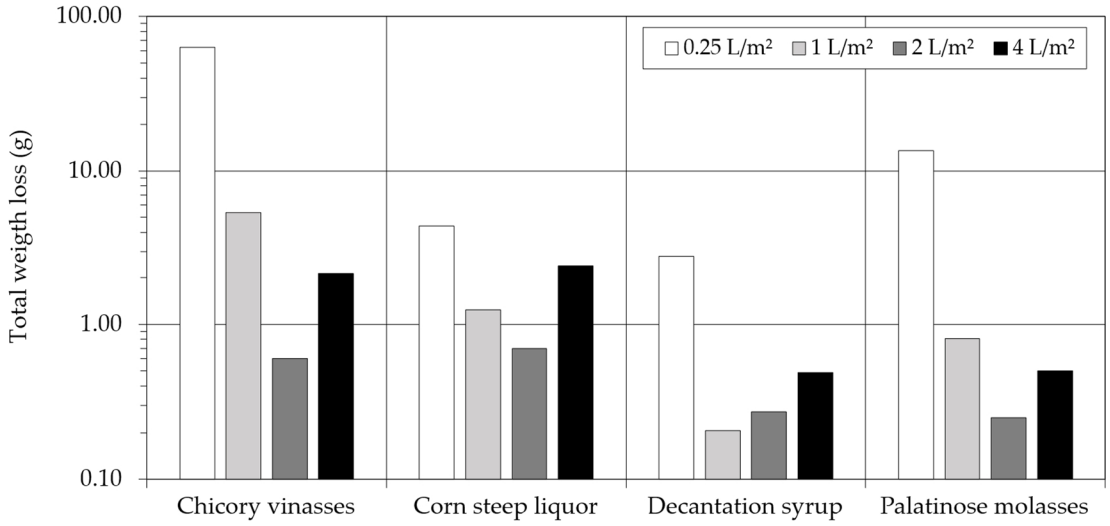


Figure 4-5. Wind-induced total weight loss of treated mine soils wetted with four different rainfall intensities after four wet–dry cycles (mean values, n = 3). By comparison, untreated soil showed a total weight loss of 125.28 g after four measuring cycles.

4.3.1.2 Effect of Wet–Dry Cycles on Wind-Induced Soil Losses

Figure 4-6 depicts the effect of wet-dry cycles on wind-induced soil losses of biomaterial-treated sand wetted with different rainfall intensities. Each bar represents the calculated mean of three replicates. It is apparent from the diagrams (Figure 4-6) that (i) the soil losses varied for each wet-dry cycle and rainfall intensity, and (ii) the biomaterials behaved differently. Chicory vinasses and corn steep liquor showed similar characteristics at a rainfall intensity of 0.25 L/m². The lowest soil losses occurred after the first wet-dry cycle, while a considerable increase was observed after the fourth. Samples treated with decantation syrup behaved slightly differently, whereby the soil losses achieved their minimum at wet-dry cycle 3 and its peak at wet-dry cycle 4. By contrast, the weight losses of palatinose molasses-treated soil peaked at wet-dry cycle 1, then decreased and subsequently increased at wet-dry cycle 4 (at a similar level to wet-dry cycle 1). At higher rainfall intensities (1–4 L/m²), the mass loss data followed no clear trend. Either the soil losses per wet-dry cycle did not differ significantly, or there were isolated outliers. In part, samples showed almost no soil losses with increasing wet-dry cycles. Detailed laboratory test data are given in Tables C-1 to C-8 of Appendix C.

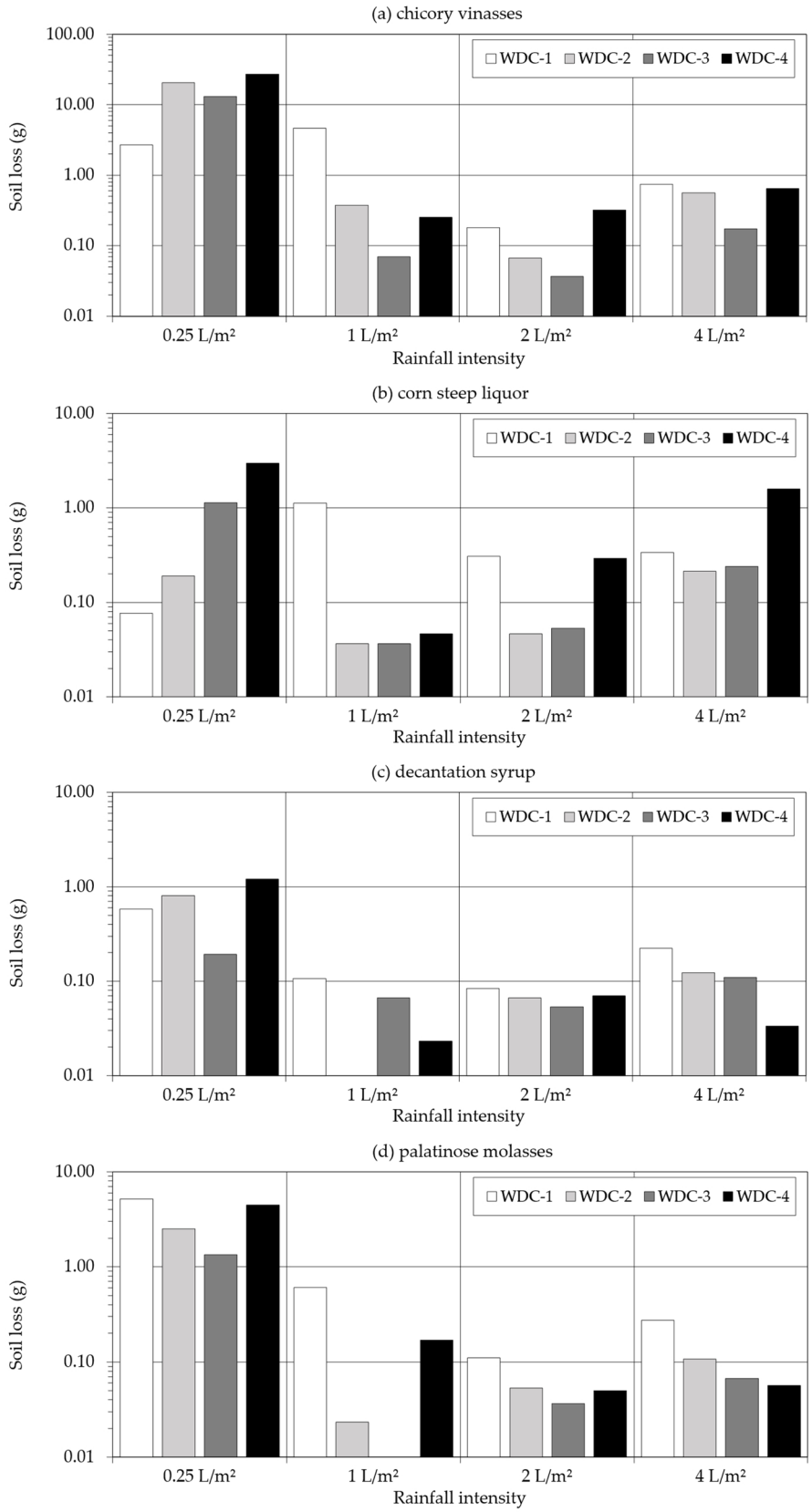


Figure 4-6. Effect of wet–dry cycles on wind-induced soil losses from mine soils treated with different food processing by-products (mean values, n = 3): (**a**) chicory vinasses, (**b**) corn steep liquor, (**c**) decantation syrup, and (**d**) palatinose molasses. Abbreviation: WDC-1 = Wet-Dry Cycle 1, WDC-2 = Wet-Dry Cycle 2, WDC-3 = Wet-Dry Cycle 3, WDC-4 = Wet-Dry Cycle 4.

4.3.2 Field Trials

4.3.2.1 Measured Dust Concentrations

Figure 4-7 illustrates the concentrations of dust particle sizes ($PM_{2.5}$, PM_{10}, TSP) measured for soils treated with different biomaterial solutions. Each bar represents the calculated mean value from triplicate analyses. The data demonstrate that mine soils treated with any of the biomaterials showed a significant reduction of dust emissions after 3 days. With increasing exposure time, dust emissions increased steadily and peaked 21 days after the solutions were applied. By comparison, data of water-treated and untreated mine soil show a different trend. The highest dust emissions were recorded on day 3 and continued to decline subsequently. In some cases, dust emissions of the control group (i.e., water-treated and untreated mine soil) achieved lower PM concentrations than treated soil samples. For example, untreated mine soil emitted less dust emissions on day 21 onwards than all test plots prepared with biomaterials.

Peak values of biomaterial-treated plots were significantly lower than those of the control group (i.e., water-treated and untreated soil). For untreated soil, PM_{10} emissions amounted to 59.026 mg/m³ ($PM_{2.5}$: 32.078 mg/m³, TSP: 77.075 mg/m³). Soil treated with pure water achieved a PM_{10} concentration of 27.649 mg/m³ ($PM_{2.5}$: 20.981 mg/m³, TSP: 39.176 mg/m³). By contrast, applications of palatinose molasses and corn steep liquor allowed to decrease PM_{10} emissions to 5.003 mg/m³ ($PM_{2.5}$: 3.152 mg/m³, TSP: 8.482 mg/m³), respectively, 3.184 mg/m³ ($PM_{2.5}$: 2.351 mg/m³, TSP: 5.169 mg/m³). In comparison, chicory vinasses and decantation syrup reduced PM_{10} emissions to 2.148 mg/m³ ($PM_{2.5}$: 1.863 mg/m³, TSP: 2.697 mg/m³) and 1.756 mg/m³ ($PM_{2.5}$: 0.900 mg/m³, TSP: 2.896 mg/m³), respectively. Among the investigated biomaterials, decantation syrup demonstrated the highest effect on reducing $PM_{2.5}$ and PM_{10} emissions after 21 days, while chicory vinasses was the most effective additive in suppressing TSP emissions. The lowest dust emissions were measured for all soil plots, including the control group (i.e., water-treated and untreated mine soil), 28 days after soil treatment. A summary of mean dust particle concentrations in air as detected during the field trial from variously treated mine soils is shown in Tables C-9 to C-11 of Appendix C.

4.3.2.2 Visual Inspection of Soil Surfaces

Figures 4-8, 4-9 and 4-10 illustrate the typical surface characteristics of eroded soils as observed during the field trials. Surfaces of the control group (i.e., water-treated and untreated mine soil) and the treated soil samples changed differently over time. Soil surfaces prepared with food processing by-products showed minor indications of wind erosion (i.e., disturbance of soil surfaces, removal of smaller soil particles) after 14 days and 21 days, respectively, without any significant changes in horizontal soil thickness (Figures 4-9 and 4-10). By contrast, plots with water-treated and untreated soil formed a conical-shaped depression that expanded slightly in depth over time (Figure 4-8). The highest soil losses were observed at the beginning of the study. Almost each test plot indicated wildlife tracks that can be attributed primarily to birds. One of the water-treated plots had to be removed from the field trial after seven days because it was extensively damaged. On day 28, all specimens appeared to have a high moisture content, and their surfaces showed visible traces of raindrops and thus were exposed to obvious rainfall events.

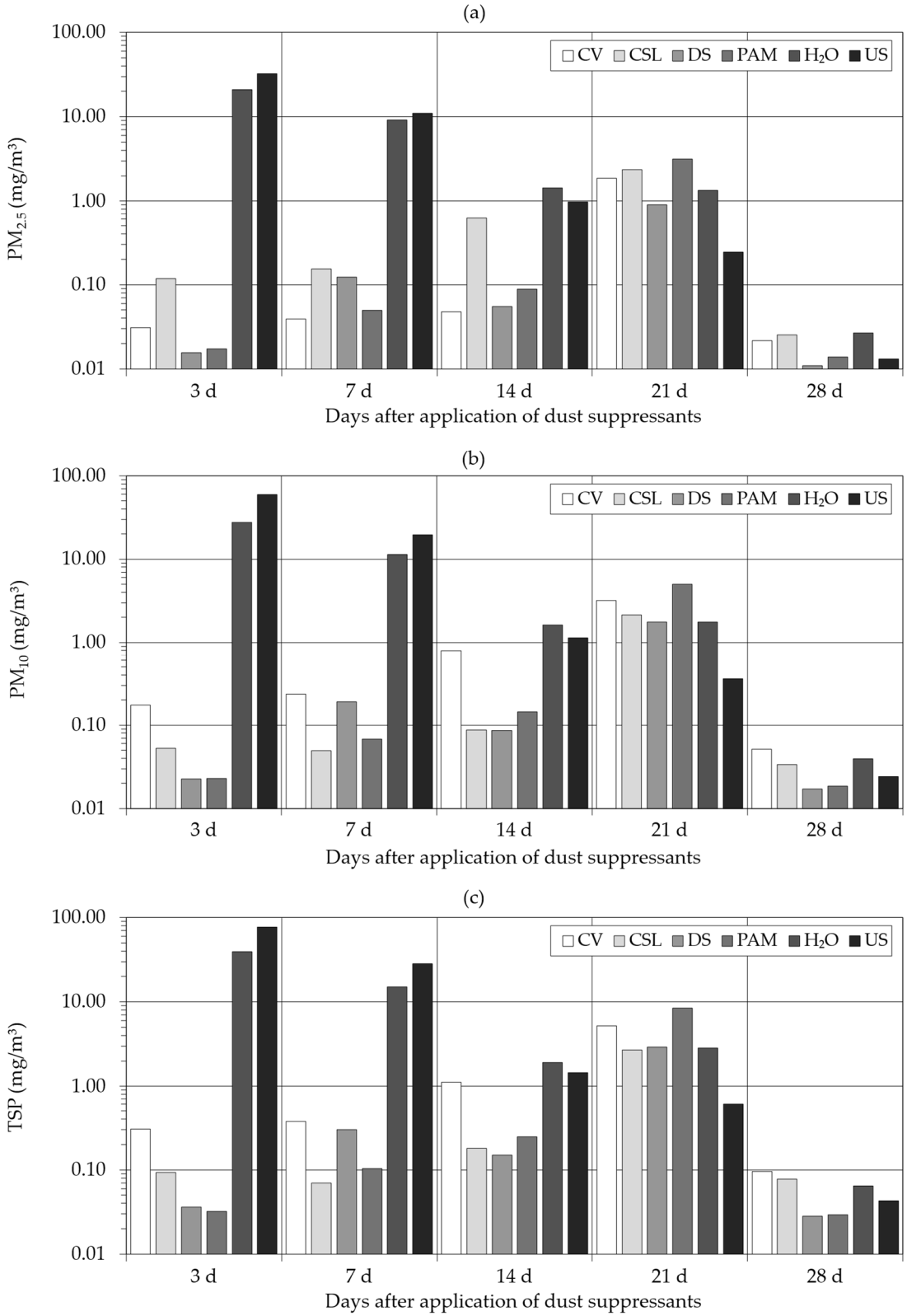


Figure 4-7. Wind-induced dust emissions from treated and untreated mine soils (mean values, n = 3): **(a)** $PM_{2.5}$, **(b)** PM_{10}, and **(c)** TSP. Dust emissions were measured 3, 7, 14, 21, and 28 days after application of dust suppressants. Abbreviations: CV = Chicory Vinasses, CSL = Corn Steep Liquor, DS = Decantation Syrup, PAM = Palatinose Molasses, H_2O = Water-Treated Soil, US = Untreated Soil.

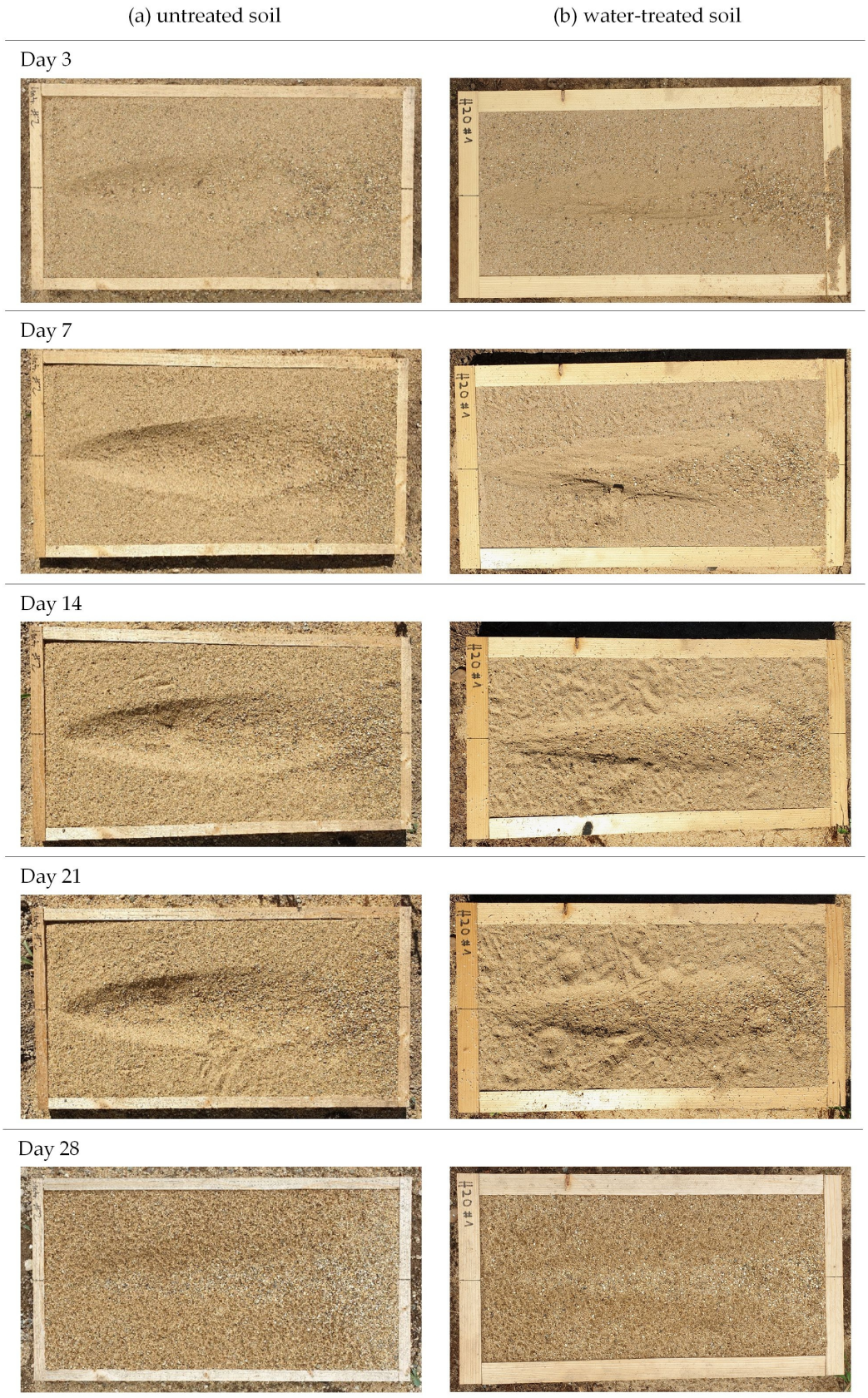


Figure 4-8. Photographic images of soil surfaces observed on day 3, 7, 14, 21 and 28 after the dust suppressants were applied: **(a)** untreated soil, and **(b)** water-treated soil. The size of each plot is 0.7 m x 0.4 m.

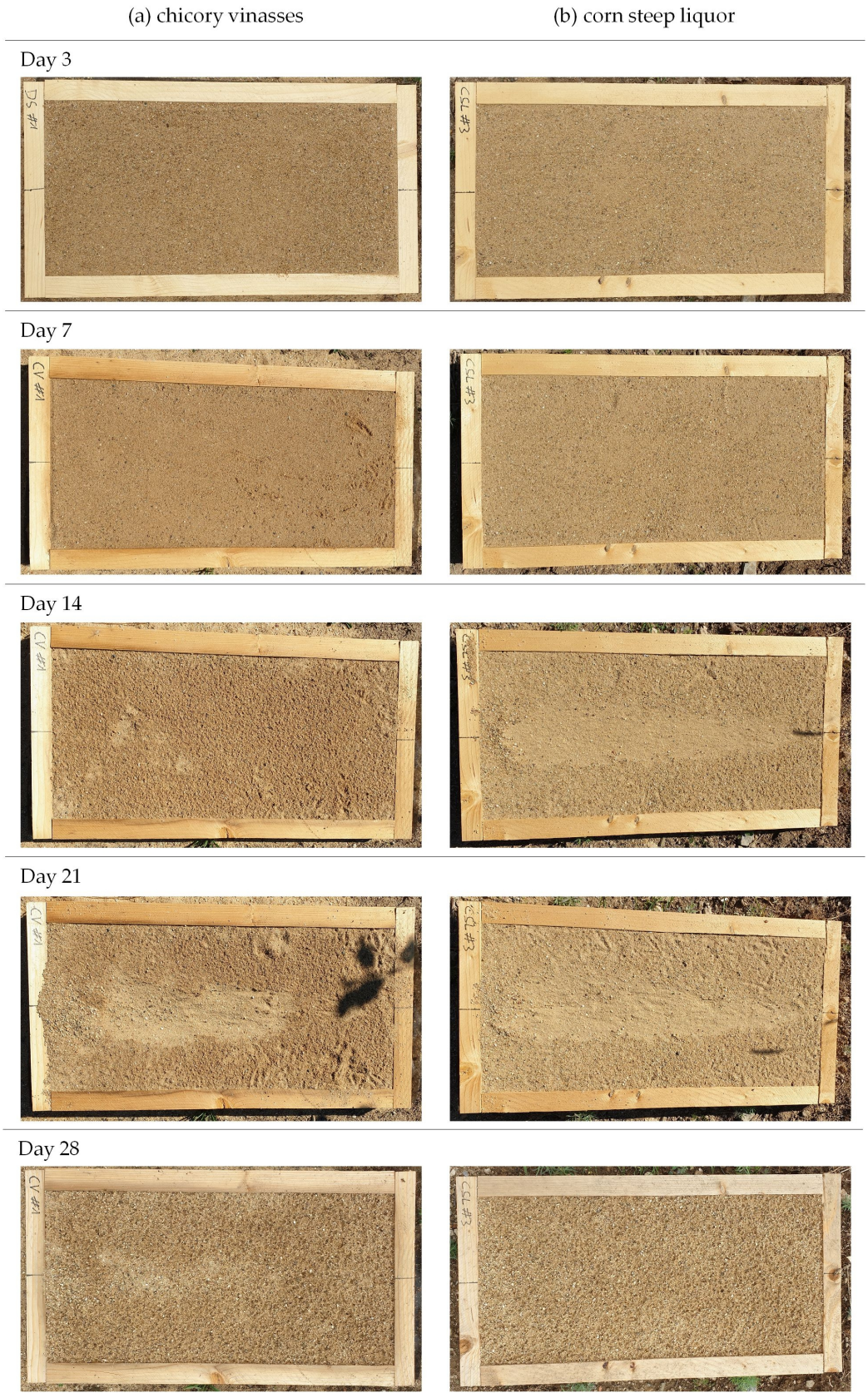


Figure 4-9. Photographic images of soil surfaces observed on day 3, 7, 14, 21 and 28 after the dust suppressants were applied: **(a)** chicory vinasses, and **(b)** corn steep liquor. The size of each plot is 0.7 m x 0.4 m.

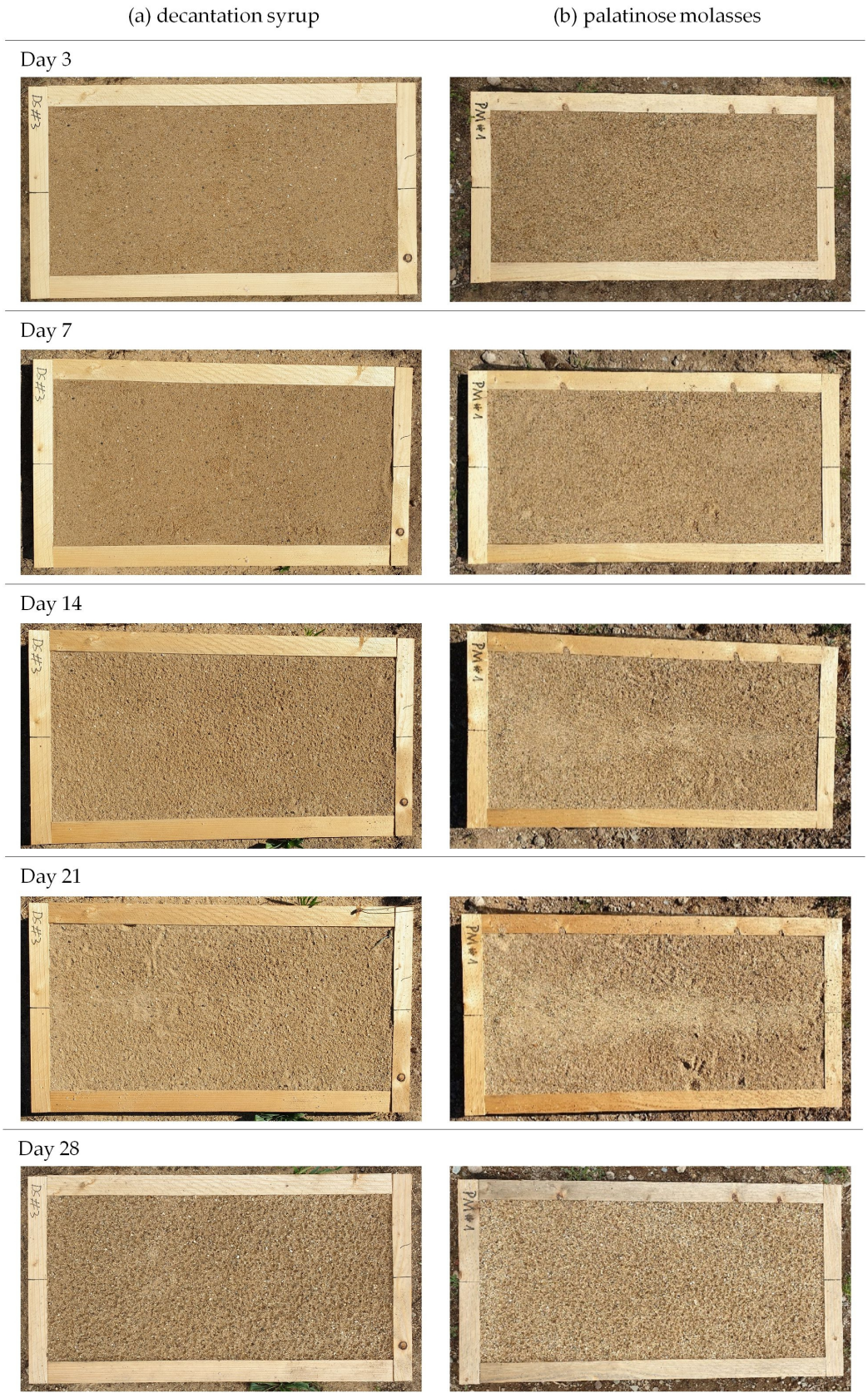


Figure 4-10. Photographic images of soil surfaces observed on day 3, 7, 14, 21 and 28 after the dust suppressants were applied: **(a)** decantation syrup, and **(b)** palatinose molasses. The size of each plot is 0.7 m x 0.4 m.

4.4 Discussion

4.4.1 Laboratory Experiments

Results of this study demonstrate that exposure of treated mine soils to different rainfall intensities influenced the amount of soil loss. In particular, increasing rainfall intensities from 0.25 to 4 L/m² led to decreasing soil losses (Figure 4-5). Possible explanations for this reduced wind erosion might be that greater amounts of applied water led to greater particle cohesion in treated mine soils or that the infiltrated water has not completely evaporated. As shown in several studies (Chen et al. 1996; Bisal and Hsieh 1966; Yuge and Anan 2019), higher moisture content improves soil cohesion and thus the resistance to wind erosion. The increase in soil cohesion can be attributed to adsorptive and capillary forces (Chen et al. 1996; Fécan et al. 1999). Regardless, it appears that more water retained in the soil samples improved the inter-particle bonding. This effect might be intensified by the food processing by-products as they consist of carbohydrates and proteins, which can augment the water retention capacity of soils and retard moisture loss from soils (Chen et al. 2015; Toufigh and Ghassemi 2020).

By contrast, exposure of treated samples to repeated wet-dry cycles resulted in increased soil losses and thus reduced the effectiveness of tested food processing by-products to suppress dust emissions (Figure 4-6). It appears that water applied at frequent intervals leached the water-soluble amendments from the substrates to such an extent that it reduced the cohesion between soil particles. This created soil surfaces that were less resistant to aerodynamic lift forces and saltation bombardment, resulting in higher soil losses. In fact, saltating sand grains are mainly responsible for aeolian dust entrainment. (Kok et al. 2012; Lu and Shao 1999; Shao et al. 1993).

Further analysis of the soil loss data (Tables C-1 to C-8, Appendix C) reveals differences between the food processing by-products in their susceptibility to leaching. While chicory vinasses showed the highest soil losses, palatinose molasses, corn steep liquor and decantation syrup were less prone to leaching. Such different responses to wetting and rainfall intensities may be explained by the composition of the tested additives. Chosen biomaterials comprise mixtures of carbohydrates and proteins, which have different affinities to water molecules. Mono- and disaccharides provide multiple hydroxyl groups that form hydrogen bonds with water (BeMiller 2019). Structural features such as branching structure, charged groups and molecular weight affect the solubility of polysaccharides, which can promote or hinder intra- and intermolecular association (Xu 2017). Protein solubility is primarily influenced by the hydrophobic and hydrophilic amino acid residues exposed to water (Zayas 1997; Kumitch et al. 2020). However, it is not possible to explain why some biomaterials are more water-soluble than others because the exact material compositions are not accessible.

4.4.2 Field Trials

Field experiments are subject to interferences that need to be considered when interpreting and comparing the effectiveness of dust suppressants. The test site is located close to an open-pit mine and to other sources of PM (e.g., unpaved roads), which could have led to dust deposition between measurements. However, it can be expected that such an additional dust input would have impacted all soil plots in a similar manner. Observed physical impairments of soil plot surfaces caused by wildlife may also be a potential source of error (Figures 4-9 and 4-10). Disturbances affect the erodibility of soil

surfaces and thus the generation of dust emissions (Belnap and Gillette 1998; Zhang et al. 2006). Consequently, results should be interpreted cautiously as to which amendments were most effective in suppressing dust emissions.

Conducted field trials demonstrate that investigated food processing by-products can significantly reduce wind erosion and dust emissions ($PM_{2.5}$, PM_{10} and TSP) from coarse mine soils (Figure 4-7). The observed decrease in dust emissions is likely attributed to carbohydrates and proteins contained in the tested amendments, which agglomerate soil particles through adhesive and cohesion forces. The aforementioned carbohydrates and proteins likely bind to soil particles upon evaporation of applied solutions. The resulting improvement in inter-particle bonding enhances the soil's mechanical properties, creating a surface with a higher erosion threshold (Freer et al. 2022a).

Field trial data also demonstrate that dust emissions from soil plots treated with food processing by-products progressively increased with time. Such a decrease in dust suppression effectiveness probably resulted from reactions at the soil surface, which weakened the bonding between soil particles and thus reduced the resistance to wind erosion. It is assumed that rainfall during the study period (Table 4-2) has resulted in the leaching of the amendments from the soils since they are water-soluble. However, visual inspections of treated soil plots show intact surfaces unlike that of the untreated soil (Figures 4-8 to 4-10). Hence, natural rainfall did not impact on the integrity of treated soil surfaces, allowing amendments to bind surficial soil particles and prevent their erosion.

By contrast to the treated soil plots, dust emissions from the untreated mine soil and mine soil treated only with water constantly decreased with time (Figure 4-7). These trends can be explained by the observed changes in surface textures (Figures 4-8 to 4-10) and the experimental setup. Near-surface wind velocity is crucial for the dynamics of wind erosion (Zhang et al. 2019). Soil particles are detached and transported when the aerodynamic drag and lift forces exceed the gravitational and inter-particle forces (Shao and Lu 2000). Moreover, dust particles are entrained by the impact of saltating sand grains (Kok et al. 2012). During the study period, erosion of the control group plots formed conical-shaped depressions and changes in horizontal soil thickness (Figure 4-8). In parallel, the position and orientation of the electric blower did not change. Hence, it is assumed that the wind velocity at the soil surface decreased over time, which reduced the forces available to erode soil and consequently dust emissions from water-treated and untreated soil plots.

At the end of the field trial (i.e., after 28 days), the lowest dust concentrations in air were measured for all soil plots, including the control group. From the meteorological data (Table 4-2), it can be concluded that previous rainfall (i.e., 27.7 L/m^2 between the days 25-27) significantly incased the moisture content of the soil. Soil moisture directly contributes to soil cohesion and substantially affects the resistance to wind erosion (Chen et al. 1996). It is generally recognized that an increase in inter-particle forces is induced by absorbed water film and capillary forces (Fécan et al. 1999). However, Ravi et al. (2004) state that capillary forces are mainly responsible for increasing cohesion forces in sandy soils, and water adsorption around the soil particles can be neglected when the soil is relatively wet.

Only a few studies have conducted field experiments simulating wind erosion on exposed mine soils treated with biodegradable reagents. Hence, only limited field

trial data on dust suppressants exist to compare the study results. Chang et al. (2020) have already stated a lack of studies evaluating the durability and reliability of biopolymers for geotechnical applications (i.e., dust control, soil stabilization, erosion control) under field conditions. For example, Park et al. (2019) tested two biocompatible polymers, polyethylene glycol and poloxamer, to suppress wind-blown dust emissions from bauxite tailings substrate. Their experiments showed that polyethylene glycol and poloxamer solutions could reduce PM_{10} emissions by up to 44 % and 66 %, respectively, compared to water-treated samples. Katra (2019) demonstrated similar performances for calcium lignosulfonate and tree resin on bedding substrate used for unpaved roads in a calcareous quarry. Conducted wind tunnel experiments indicated a 63 % and 53 % reduction in PM_{10} emissions from lignosulfonate and tree resin solutions, respectively, compared to untreated samples (Katra 2019). However, only limited conclusions can be drawn due to partially substantial distinctions in experimental design, substrate type, climatic conditions, and other factors. Regardless, chosen food processing by-products display a distinct ability to suppress PM emissions in the field (Figure 4-7).

4.4.3 Possible Applications of Food Processing By-Products as Dust Suppressants at Mine Sites

4.4.3.1 Technical Aspects

The present study demonstrates that food processing by-products can considerably suppress dust emissions from sandy mine soils (Figure 4-7). However, the results also demonstrate that the tested biomaterials are more likely to be used only for temporary or short-term dust control practices due to their susceptibility to be leached from soil surfaces upon rainfall events and possible degradation in the environment. Factors that may contribute to the degradation of biomaterials include solar radiation, heat, abiotic oxidation, biotic reactions of microorganisms and saltating soil particles' impact force (Briassoulis 2005; Göpferich 1996; Piechota et al. 2004; Gillies et al. 1999; Tian and Bilal 2020). Repetitive application of the amendments to mine soils may counteract their diminishing dust control effectiveness over time.

Considering their water-solubility, tested amendments could either be sprayed on substrate surfaces or incorporated into mine soils, which is usually applied on traffic areas (Piechota et al. 2004). This method involves higher single application costs but extends the service life of treatments (Thompson and Visser 2007; Rushing and Tingle 2007). However, it appears challenging to exploit this durability benefit due to amendments' susceptibility to leaching and biodegradability.

Promising is the fact that the tested reagents could likely be applied using existing application equipment (e.g., water trucks with spray bars), already available at many mine sites. The biomaterials readily dissolve in water and have not notably impaired the rheology of the aqueous solution. By contrast, thermal-gelling biopolymers, such as gellan gum or agar gum, require heated water to be dissolved or applied, respectively, and yield highly viscous solutions even at low concentrations (Mudgil et al. 2014; Chang et al. 2016a). As Chang et al. (2020) already stated, any application equipment may need to be modified or developed considering the rheological properties of biopolymers.

The tested biomaterials contain carbohydrates and proteins, which promote seed germination and plant growth and serve as sources of energy for soil bacteria (Chang et al. 2015d; Pylak et al. 2019). Therefore, an application of food processing by-products can

provide nutrients to plants while simultaneously stabilizing the soil surface until the vegetation cover has been developed. Hence, the use of food processing by-products in mine closure and mine site rehabilitation activities might also support revegetation efforts of mined lands.

4.4.3.2 Financial Considerations

The application of food processing by-products as dust suppressants appears to have financial benefits compared to commercially available biopolymers. By-products from the food industry are usually inexpensive, generated in high volumes, and readily available (Jõgi and Bhat 2020; Anal 2017; Mahro et al. 2015). Chicory vinasses, for example, is priced at less than 100 $/t (Range 2021). By contrast, the biopolymer xanthan gum, extensively investigated for soil stabilization and wind erosion control in previous studies, ranges in price from 1500 to 4000 $/t (Chang et al. 2020; Chang et al. 2015b). However, growing demand for biopolymers and the associated increase in production volume are expected to reduce biopolymer prices in future (Chang et al. 2016b; Chang et al. 2015b; Chang et al. 2020).

Specific emphasis should be paid to equipment operating costs, which can frequently escalate the total costs of dust suppression (Thompson and Visser 2003). Here, significant cost drivers include suppressants' durability and their related re-application intervals required to sustain a sufficient level of dust control (Thompson and Visser 2007). Compared to biopolymers, tested biomaterials will likely need shorter re-applications intervals because rainfall may leach them from surface substrates more easily. Some biopolymers have thermal-gelation properties, such as gellan gum or agar gum, which only dissolve entirely in hot water (Chang et al. 2015c). Likewise, proteins (e.g., casein) with lower hydrophilicity probably provide higher resistance to rainfall and subsequent leaching (Chang et al. 2018). However, a reliable cost-effectiveness assessment requires further research, considering biomaterials durability, application intervals and application rates. One possible approach to progress this knowledge would be the economic evaluation model developed by Thompson and Visser (2007), which enables the costing of the establishment, application and maintenance activities associated with the use of dust suppressants.

4.4.3.3 Environmental Issues and Implications

Even though this study shows encouraging results for applying food processing by-products as dust suppressants, potential adverse effects and issues associated with a future application on mine soils need to be considered. Rainfall events could leach the tested biomaterials through soils to receiving ground and surface waters, adding an organic load to aquatic ecosystems (Singh et al. 2003; Kunz et al. 2022). Organic matter decreases dissolved oxygen concentration in freshwater bodies due to bacteria and other microorganisms' growth, resulting in stresses on aquatic life (Li et al. 2021). Also, carbohydrates and proteins in the tested reagents could attract animals and insects or cause problems with mold growth on the treated surface or inside the application equipment (Jones 2017; Edvardsson et al. 2012).

If such amendments are applied to tailings surfaces, further problems could arise. Recycled water from tailings storage facilities may contain appreciable concentrations of dust suppressant residues, which could adversely affect mineral processing methods such as flotation due to reactions with other reagents (Park et al. 2019). Park et al. (2019)

also remarked that polymers could impair tailings ponds stability because of augmented water retention and associated changes in substrate properties (e.g., pore pressure).

4.4.4 Outlook

Any comparison of field trial data on dust suppressants is hampered by the fact that different studies pursue individual experimental designs and measurement methods. Hence, there is a clear need for standardized simulated dust suppression tests that provide information that can be used to predict dust emissions from soils. Such a method would be used to determine probable dust dispersion and develop cumulative dust emission and suppression data to support mine permit application requirements. Those methods could also be tools to generate data used to design and implement best management practices and treatment processes needed by mining operations to meet compliance requirements.

In the mining industry context, a standard testing methodology should be feasible in remote and relatively inaccessible areas (e.g., tailings sites), easy to implement and allow for comparative sampling of various dust control products with minor financial and personnel requirements. Accordingly, experimental setups with field boundary layer wind tunnels, usually used to quantify dust emissions from soils, are not expedient because they are difficult to transport, labor-intensive and pose substantial methodological challenges (McKenna Neuman et al. 2009; Kavouras et al. 2012).

By contrast, methodologies adopting soil plots eroded with commercial electric blowers do pose suitable alternatives, even though measured dust emissions do not reflect dust emissions caused by natural wind erosion since electric blowers do not simulate the atmospheric flow. Those experiments can establish the effectiveness of dust suppressants over different test intervals at locations where they are intended to be applied, indicative of possible commercial-scale application and practice (Kavouras et al. 2012). Moreover, such field trials are easy to conduct and enable cost-effective and low-maintenance testing of various soil treatments with replicates. Future steps that need to be taken to establish a standardized methodology are (i) harmonization of experimental parameters (e.g., applied wind speed, exposure time to simulated wind erosion) and sample preparation, and (ii) definition of requirements on electric blowers (e.g., outlet diameter), dust monitors and test site. It is also recommended to compare measurements of the proposed methodology with the portable in-situ wind erosion lab (PI-SWERL) concept. The PI-SWERL is a cost-effective method to assess the potential of soil surfaces to generate dust emissions and correlates with traditional wind tunnel tests (Etyemezian et al. 2007).

4.5 Conclusions

This study investigated the effectiveness of four biodegradable by-products from the food industry in suppressing fugitive dust emissions from mine soils. The following main conclusions can be drawn:

- Carbohydrate- and protein-rich by-products from food processing reduce PM emissions from sandy mine soils as tested in the laboratory and field trials, indicating their potential to be applied as dust suppressants at mine and mineral processing sites.

- Rainfall impairs the effectiveness of tested biomaterials due to progressive leaching and loss of amendments from treated soils. While rain may decrease additives' concentration in surface layers, treated soil surfaces remain physically intact.
- Soil loss data from laboratory tests indicate that biomaterials' effectiveness decreases with repetitive wet-dry cycles. Exposure of treated mine soils to increasing rainfall intensities led to decreasing soil losses, possibly due to enhanced inter-particle bonding, incomplete evaporation of infiltrated water or augmented water retention capacity of the soil.
- There is a clear need for standardized simulated dust suppression tests.

In conclusion, this study demonstrates that food processing by-products can be used for short-term dust mitigation at mine and mineral processing sites. Their application as dust suppressants would reduce dust control expenses and diminish chemical products detrimental to the environment.

Chapter 5
General Discussion, Conclusions, and Recommendations

The final chapter contextualizes the research findings within academic discourse and integrates them into the broader context of dust suppressant application. It begins by addressing the central research question, followed by a SWOT analysis to evaluate the competitive position of food processing wastes and by-products in the dust suppressant market. The chapter then draws out both theoretical and practical implications and concludes with recommendations for future work.

5.1 Answers to the Central Research Question

This section synthesizes the research results to address the central research question. Starting with a concise overview of the current state of knowledge in the field, it restates the identified research gap and the guiding central research question before discussing the key findings.

5.1.1 Summary of the Current State of Knowledge

A review of existing literature on dust suppressant research highlights the critical need for environmentally friendly, low-cost and easily applicable substances capable of effectively suppressing wind-blown dust emissions. One promising strategy to identify such materials involves analyzing wastes and by-products generated during food processing. This approach is justified by several key characteristics of these materials: they are biodegradable, abundantly available, exhibit rapid dissolution in cold water without compromising viscosity, and are inexpensive to acquire (Anal 2017; Ribeiro et al. 2022; Jõgi and Bhat 2020; Torres-León et al. 2018; Caldeira et al. 2019). Most significantly, food processing wastes and by-products are rich in carbohydrates and proteins, which have been demonstrated to potentially restrict the release of dust particles into the atmosphere caused by wind erosion (Jõgi and Bhat 2020; Lemboye et al. 2021; Nouri et al. 2022; Omane et al. 2017; Owji et al. 2021).

The ability of substances to suppress wind-blown dust emissions is predominantly investigated through laboratory-based tests. These experiments evaluate how substances influence the soil's mechanical strength and resistance to wind erosion. However, a major limitation of current research is the lack of data collected under real-world conditions (Katra 2019; Chang et al. 2020). Field experiments are of crucial importance given the significant influence that environmental factors can have on the effectiveness of dust suppressants over time (Gillies et al. 1999). At present, there is limited understanding of how abiotic and biotic factors impact the effectiveness of carbohydrate- and

protein-based materials over time, at what application rates and concentrations they are effective, and the frequency at which re-application is required to maintain adequate dust suppression.

In the literature, various methods have been described to assess soil strength. The UCS test is used frequently, measuring the maximum axial compressive stress that an unconfined cylindrical soil sample can withstand (DIN EN ISO 17892-7:2018-05) Additional methods of evaluating soil strength include shear strength tests and penetration resistance tests (Sieger et al. 2023c; Huang et al. 2008; Xu et al. 2018; Liu et al. 2011; Sieger et al. 2023b). A substantial body of research has repeatedly demonstrated that carbohydrate- and protein-based materials can significantly enhance soil strength, indicating their ability to agglomerate soil particles, which is one mechanism by which dust suppressants act (Soldo et al. 2020; Chang et al. 2018; Chen et al. 2016; Choi et al. 2020; Fatehi et al. 2018; Soldo et al. 2022; Xu et al. 2018; Parvej et al. 2021). Studies carried out to date have investigated a variety of commercially available carbohydrates and proteins applied across different soil types and concentrations.

The effectiveness of materials in forming erosion-resistant soil surfaces is typically investigated using wind erosion tests. In these experiments, treated soil samples are placed into a laboratory-based wind tunnel and exposed to simulated airflow. The loss of soil is measured to quantify the resistance of the soil to wind erosion. Some studies also incorporated wetting–drying cycles to simulate the effects of rainfall and investigate its influence on erosion resistance. These include the works of Ayeldeen et al. (2017), Chen et al. (2015), and Toufigh and Ghassemi (2020). Recent research has reported substantial reductions in soil loss following the application of carbohydrate- and protein-based treatments (Chen et al. 2015; Lemboye et al. 2021; Nouri et al. 2022; Ayeldeen et al. 2017; Toufigh and Ghassemi 2020; Owji et al. 2021; Omane et al. 2017; Kavazanjian et al. 2009). A range of commercially available carbohydrates and proteins, application rates and concentrations, soil types, and testing durations were examined in these studies.

5.1.2 Restatement of the Research Gap and the Central Research Question

Food processing wastes and by-products show promise to function as dust suppressants, however, to date, only a few studies have assessed their effectiveness in reducing dust emissions. These include the works of Gotosa et al. (2015), Parsakhoo et al. (2020), Omane et al. (2017), and Liu et al. (2022). This lack of research highlights the need for further investigation to enhance our understanding of the limitations and potential use of these materials as dust suppressants.

In order to address the gap in the literature, this thesis aims to evaluate the effectiveness of food processing wastes and by-products in suppressing wind-blown dust emissions from exposed mine soils. The central research question guiding this work is as follows:

What is the potential for food processing wastes and by-products to be used as dust suppressants in the control of wind-blown dust emissions from exposed mine soils?

The research was conducted in three stages, each building upon the findings of the previous one, to address the central research question. In all experiments, conventional watering was chosen as a benchmark because of its continued prevalence as the

primary method for dust control in the mining industry. The results were disseminated through two peer-reviewed articles (Chapters 2 and 4) and one pre-print (Chapter 3).

5.1.3 Discussion of the Key Findings

Chapter 2 provided first indications as to whether food processing wastes and by-products have the potential to function as dust suppressants. A series of UCS experiments were conducted with sixteen food processing wastes and by-products to analyze their ability to agglomerate soil particles. The data demonstrated a significant enhancement in soil strength following treatment. While untreated soil had a UCS of 11 kPa, the most effective materials achieved strengths between 1,366 and 2,026 kPa, with one material attaining 7,535 kPa. These values match or exceed the performance of commercial biopolymers reported in the literature (Soldo et al. 2020; Chang et al. 2016a; Fatehi et al. 2018). However, it is important to recognize the limitations of direct comparisons across studies, as experimental conditions such as curing time, curing temperature, and additive concentration often differ considerably (Huang et al. 2008; Elkady 2015; Latifi et al. 2016; Tingle and Santoni 2003).

Among tested food processing wastes and by-products, palatinose molasses, which is primarily composed of disaccharides, had the greatest enhancement in mechanical strength. This finding contrasts with the current research emphasis on protein- and polysaccharide-based materials for environmentally friendly dust suppression and suggests that certain simple sugars may warrant further investigation.

The results further indicated that food processing wastes and by-products rich in proteins and polysaccharides have greater potential to function as dust suppressants than those dominated by low molecular weight carbohydrates, as reflected in their higher average UCS values. In contrast, food processing wastes and by-products primarily composed of glucose and fructose exhibited only marginal improvements in soil strength, suggesting only a minimal potential for dust suppression through soil particle agglomeration.

Chapter 3 extended the research by evaluating the ability of food processing wastes and by-products to modify soil surfaces to resist wind erosion. Treated soil samples were subjected to a steady airflow of 13.57 m/s in a laboratory wind tunnel. This was repeated at regular intervals over a 28-day period. The results demonstrated that mine soil surfaces can indeed be stabilized against erosive forces through the application of food processing wastes and by-products, with all treatments achieving a soil loss reduction exceeding 99 %. By comparison, traditional watering mitigated less than 39 % of wind-induced soil loss. These findings serve to reinforce the conclusions previously drawn from UCS testing and provide further evidence for the hypothesis that wastes and by-products from food processing can suppress wind-blown dust through soil particle agglomeration.

Subsequent statistical analysis using ANOVA confirmed that both the application rate ($p < 0.001$) and additive concentration ($p < 0.001$) have a significant effect on soil loss. In general, increasing either parameter led to improved erosion resistance. However, the data also revealed optimal thresholds for each material, beyond which further increases in concentration or application rate produced only marginal or no additional benefits. Comparative analysis with existing studies on commercially available biopolymers suggested that food processing wastes and by-products may require higher dos-

ages per unit area to achieve similar levels of effectiveness (Lemboye et al. 2021; Kavazanjian et al. 2009; Owji et al. 2021; Sieger et al. 2023b). Maximum soil loss reduction was typically observed at additive concentrations between 5 % and 10 %, applied at application rates ranging from 0.75 to 1.5 L/m².

Chapter 4 completed the research by exploring how environmental conditions affect the effectiveness of food processing wastes and by-products in establishing wind erosion-resistant soil surfaces. This investigation is of particular significance given the considerable impact of abiotic and biotic factors on the durability of dust suppressants, offering critical insights towards the main research question (Gillies et al. 1999).

The study began with laboratory-based leaching experiments, in which treated soil samples were subjected to multiple wetting-drying cycles combined with varying simulated rainfall intensities (0.25–4 L/m²), followed by exposure to a laminar airflow of 13.57 m/s in a wind tunnel. Results demonstrated that, despite their vulnerability to water, food processing wastes and by-products were capable of forming wind erosion-resistant soil surfaces. However, their effectiveness declined under simulated rainfall, as indicated by increased soil loss.

Subsequently, field experiments were conducted over a 28-day period at an open-pit lignite mine. Soil plots were regularly exposed to wind erosion (14.65 m/s) using a commercial electric blower. Results confirmed the ability of food processing wastes and by-products to establish erosion-resistant surfaces under real-world conditions, as their application to mine soil significantly reduced particulate emissions. Specifically, reinforced soils exhibited PM_{10} concentrations ranging from 1.7 to 5.0 mg/m³ ($PM_{2.5}$: 0.9–3.2 mg/m³; TSP: 2.7–8.5 mg/m³), whereas untreated soil and water-treated soil showed PM_{10} levels of 59.0 mg/m³ ($PM_{2.5}$: 31.1 mg/m³; TSP: 77.1 mg/m³) and 27.7 mg/m³ ($PM_{2.5}$: 21.0 mg/m³; TSP: 39.2 mg/m³), respectively.

Further analysis of the field test data revealed a progressive increase in particulate emissions over time from soils treated with food processing wastes and by-products. This escalation is likely attributed to surface weathering reactions that weakened interparticle bonding, thereby reducing its resistance to wind erosion. Meteorological data indicated that persistent rainfall substantially contributed to this decline in effectiveness by gradually leaching out the applied materials. This suggests that food processing wastes and by-products may remain effective for longer durations in regions characterized by prolonged dry periods, compared to those with frequent rainfall. In arid environments, their durability is more likely influenced by factors such as biodegradation and physical weathering rather than rainfall-induced leaching. To mitigate the observed decline in dust suppression over time, periodic re-application or the use of higher dosage rates per unit surface area is recommended.

In conclusion, soil samples treated with food processing wastes and by-products exhibited significantly greater mechanical strength and experienced a substantial reduction in wind-induced soil loss and airborne particulate emissions. These results confirm the ability of these materials in forming wind erosion-resistant surfaces through soil particle agglomeration. The research thus provides empirical evidence supporting the potential of food processing wastes and by-products as dust suppressants for mitigating wind-blown dust emissions from exposed mine soils. While environmental factors, particularly rainfall, can diminish their performance, the findings emphasize the promise of these materials as low-cost, easy-to-apply, and environmentally friendly alternatives for

dust control. However, further investigations are required to fully characterize their potential and limitations as dust suppressants.

5.2 Evaluating the Competitive Position in the Dust Suppressant Market

This section integrates the dissertation findings into a broader context of dust suppressant application. A SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is conducted to evaluate the competitive position of food processing wastes and by-products in the dust suppressant market. This framework allows us to identify unique selling points of these materials, market gaps they could fill, and potential barriers to market entry and adoption (Benzaghta et al. 2021; Helms and Nixon 2010). The analysis critically compares food processing wastes and by-products with both conventional and emerging environmentally friendly dust control solutions, with a specific focus on traditional watering, synthetic polymers and biopolymers, and highlights potential competitive advantages and disadvantages.

The results of the SWOT analysis are summarized in Table 5-1. It is important to note that the list is not intended to be exhaustive. A detailed discussion of the identified strengths, weaknesses, opportunities and threats are as follows below.

Table 5-1. Results of the SWOT analysis.

Strengths	*Weaknesses*
• Low product prices • Effective regardless of humidity level • Ease of preparation and application • Safe storage and handling • Biodegradability and non-toxicity • Reduction in water consumption • Low carbon footprint • Conservation of resources • Improvement of soil fertility	• Limited durability • High application rates and concentrations required • Variability in composition and dry matter content • Organic pollution of aquatic ecosystems • Odor emissions • Mold infestation • Attraction of animals • Adverse effects on mineral processing methods
Opportunities	*Threats*
• Growing demand for eco-friendly dust suppression solutions • Stricter standards for air quality • Carbon pricing • Increasing importance of corporate social responsibility • Partnerships and collaborations	• Competing environmentally friendly dust suppression options • Competition with other forms of utilization • Limited market awareness • Changes in the landscape of the food processing industry • Low-availability periods • Employee complaints and resistance

5.2.1 Strengths

The term "strengths" refers to product features that give an edge over existing competitors (Leigh 2009). In the author's opinion, the main strengths of using food processing wastes and by-products as dust suppressants are:

- Low product prices

- Effective regardless of humidity level
- Ease of preparation and application
- Safe storage and handling
- Biodegradability and non-toxicity
- Reduction in water consumption
- Low carbon footprint
- Conservation of resources
- Improvement of soil fertility

Low product prices

One major advantage of utilizing food processing wastes and by-products for dust suppression is that they can often be procured at very low cost (Anal 2017). This aspect is beneficial considering the significant influence the unit price of a dust suppressant has on the total expenses for a single application (Inyang et al. 2016). Low product prices can greatly enhance the cost-effectiveness of dust control measures, particularly for applications intended for short durations.

Although data availability is limited and refers to different years, it is evident that food processing wastes and by-products have remarkably lower unit prices compared to biopolymers and conventional dust control products. For example, chicory vinasses, decantation syrup and palatinose molasses, all food processing by-products evaluated in this work, are priced at $84 per tonne, $145 per tonne, and $204 per tonne, respectively (Range 2021). Waste materials from food processing facilities, such as rinsing water from jam production or filtration residues from milk protein production, can be acquired for a fraction of the cost or even free of charge (Born 2019; Möller 2019). Prices may vary seasonally or regionally based on local industry concentrations and wastes and by-products generation patterns. Moreover, the distance required to transport such products and the minimum product volumes can have a significant impact on their cost.

In contrast, prior research shows that biopolymers studied for soil stabilization and wind erosion control have significantly higher unit costs. Guar gum, xanthan gum and gellan gum, for example, range from $3,000 to $3,200 per tonne, $1,650 to $2,100 per tonne and $2,000 to $5,000 per tonne, respectively (Jang 2020). However, biopolymer prices are expected to fall in the future as their demand grows and production volumes increase (Chang et al. 2015b). Moreover, some initial research has explored the use of less expensive biopolymers as dust suppressants. Sieger et al. (2023c), for example, investigated various modified starches and hemoglobin powder, available for less than $1,000 per tonne.

Conventional and commercial dust suppressants generally have higher prices compared to food processing wastes and by-products. For instance, the unit prices of petroleum-based products, electrochemical products, and synthetic polymers range from $0.8 to $1.9 per liter, $1.3 to $3.4 per liter and $0.6 to $1.2 per liter, respectively (Dalton 2013). Edwards et al. (2010) tested several commercial dust control products, with prices averaging $1.7 per liter and ranging up to $3.7 per liter.

Effective regardless of humidity level

Unlike hygroscopic salts, the dust suppression effectiveness of food processing wastes and by-products is not dependent on a specific ambient moisture level. These materials act as dust suppressants by agglomerating soil particles. On the other hand,

hygroscopic salts achieve dust suppression by attracting and holding water molecules through absorption from the atmosphere, a process that requires a specific humidity level to be effective (Edvardsson et al. 2010). For instance, sodium chloride begins to absorb water at 76 % relative humidity (25 °C) (Han 1992). This suggests, in turn, that food processing wastes and by-products can be utilized as dust suppressants in arid and semi-arid climates, where the application of hygroscopic salts, in comparison, is not practical (Melese et al. 2018; Foley et al. 1996).

Ease of preparation and application

Food processing wastes and by-products are easy to prepare and apply as dust suppressants. The materials tested in this thesis are easily dissolved in cold water and exhibit non-viscous behavior at standard dust suppressant concentrations. Typically supplied in a concentrated form, they only require dilution to the desired concentration prior to application. This simplicity in preparation and application is comparable to that of conventional dust control products such as brines or synthetic polymers.

Recent research in the field of wind erosion control and dust suppression has focused on biopolymers such as Owji et al. (2021), Ding et al. (2020), and Jin et al. (2019), which share solubility characteristics with food processing wastes and by-products. These materials are just as easy to use as dust suppressants. However, this ease-of-use contrasts sharply with numerous biopolymers extensively studied in previous research, which often exhibit challenging solubility behaviors in water. These materials require specific pH conditions or high temperatures for dissolution. For example, gellan gum and agar gum are only fully soluble at temperatures above 80 °C and 86 °C, respectively (Chang et al. 2016a; Khatami and O'Kelly 2013). Chitosan requires an acidic environment, while casein is only soluble in alkaline solutions (Kavazanjian et al. 2009; Chang et al. 2018). These specific requirements complicate preparation and application processes, making these biopolymers less practical for dust suppression efforts on a commercial scale.

Another significant challenge posed by some biopolymers (e.g., Xanthan gum) is the formation of highly viscous solutions, even at minimal concentrations (Chang et al. 2015a). These viscous solutions cannot be applied using conventional equipment such as water trucks. Instead, modified equipment or hydroseeders, which are capable of handling even heavy and highly viscous slurries, must be utilized (Cereno et al. 2011; Emeka et al. 2021). Alternative measures include applying the solution at a higher application rate or in multiple light applications to achieve the required dosage rate. However, these approaches inevitably lead to higher costs and increased water consumption, which can reduce their economic and environmental viability.

Similarly, biopolymers such as gellan gum and agar gum that dissolve only in heated water necessitate specialized equipment for dust suppression (Chang et al. 2016a; Khatami and O'Kelly 2013). Such materials necessitate specialized equipment to ensure constant stirring and heat input, maintaining them in a dissolved state. This includes agitators to prevent settling or clumping, heating systems to maintain elevated temperatures, pumping aggregates for solution transport, and freshwater tanks for dilution and preparation. Maintaining high water temperatures give rise to increased operating costs.

Furthermore, some biopolymers, such as gelatin, can form a gel when the solution cools down (Dang et al. 2017). This gel formation can lead to operational downtime

and potential damage to the application equipment. The risk of gel formation requires careful temperature monitoring throughout the application process, further complicating the use of these materials in dust suppression.

Safe storage and handling

Food processing wastes and by-products are safe to handle and store, similar to biopolymers. There are a number of arguments supporting this conclusion. Initially, food processing wastes and by-products are generally considered harmless for human health. They are biogenic materials arising from a food production process and generated in facilities that must adhere to strict hygiene regulations, as mandated by Regulation (EC) No 852/2004 (European Union 2004). In addition, most food processing wastes and by-products are permitted for use as animal feed and undergo regular screening for potential contaminants (Anal 2017; European Union 2017). Nonetheless, to minimize any potential risks associated with exposure to them, wearing safety goggles and gloves during their handling is recommended.

According to the safety data sheets (available on the supplied SD card), no special fire and explosion protection requirements are necessary when storing and handling food processing wastes and by-products. However, it should be noted that food processing wastes and by-products supplied in powder form are combustible. Although the powders themselves are not classified as dust explosible in their supplied state, the accumulation of fine dust particles from these powders may pose a dust explosion hazard. In contrast, food processing wastes and by-products supplied as concentrates pose no fire hazard.

With exceptions, wastes and by-products from food processing have shelf-lives, allowing storage for several months to years. The decisive factor here is the microbiological stability of the material, which depends, among other things, on prevailing storage conditions. Food processing wastes and by-products require storage in cool, dry facilities without direct exposure to sunlight to inhibit the growth of microorganisms and the associated decomposition of organics into acids, gases or alcohols. Powders, such as milk permeate, containing hygroscopic components (e.g., amorphous lactose) require special storage in sealed bags to prevent them from absorbing moisture from the environment. Concentrates, such as beet molasses, should be stored undiluted, although reducing viscosity would improve its handling. A decrease in dry matter content can lead to a rapid growth of microorganisms that accelerate the degradation of organic components (safety data sheets; available on the supplied SD card).

Biodegradability and non-toxicity

A key strength of using food processing wastes and by-products for dust suppression from an environmental perspective is their general non-toxicity and biodegradability. The organic compounds they contain are broken down by microorganisms and transformed into harmless metabolic products, thereby minimizing the risk of persistence and accumulation in the environment (Zumstein et al. 2022; Nair et al. 2017).

In contrast, conventional dust suppressants are associated with adverse environmental effects. For example, polymer-based dust suppressants are designed to resist degradation, raising concerns about long-term exposure and bioaccumulation. These substances can accumulate in plants, animals and microorganisms, potentially harming or disrupting ecosystems by affecting their growth, reproduction, and survival (Zhang

et al. 2024a). On the other hand, bitumen emulsions contain several contaminants, such as naphthenic acids, polyaromatic hydrocarbons (PAHs), and metals (Robidoux et al. 2018; Dew et al. 2015). Moreover, hygroscopic salts have shown negative impacts on soil, vegetation and aquatic life. These salts can alter soil chemistry, reduce soil fertility, affect plant growth, and increase salinity levels in water bodies (Rushing and Newman 2010; Goodrich et al. 2009; Tiwari and Rachlin 2018).

Another concern with commercial dust suppressant products is the lack of disclosure surrounding their exact chemical composition, along with the limited information available on their environmental impact. This information gap is likely due to proprietary reasons (Kunz et al. 2022).

Reduction in water consumption

While traditional watering is widely used to control dust at mining and mineral processing sites, this approach suffers from notable limitations. Frequent re-application is necessary, leading to escalating water consumption (Du Plessis et al. 2016; Thompson and Visser 2007). Bolander and Yamada (1999) found that watering is typically effective for only a short period of 0.5 to 12 hours. In contrast, the application of food processing wastes and by-products requires significantly less water input while still providing adequate dust mitigation. The present research demonstrates that a single treatment with these materials can effectively reduce dust emissions from exposed mine soils for a period of up to 28 days. As climate change exacerbates water scarcity, implementing dust suppression strategies that conserve water is becoming increasingly crucial for the mining sector, which faces mounting political and community pressure to preserve water resources (Schoderer et al. 2020; Schoderer and Ott 2022).

Low carbon footprint and conservation of resources

Using food processing wastes and by-products for dust suppression has a low carbon footprint and conserves resources. A key advantage is that they are derived from renewable resources, such as crops, roots and tubers (Mateos-Aparicio and Matias 2019). These materials are also readily available regionally across Europe (Russ and Meyer-Pittroff 2004). Moreover, no additional energy, water, chemicals, or other natural resources are required to generate these food processing wastes and by-products. They arise as residual materials from existing production processes rather than being intentionally generated.

The case is different for commercial dust control products. For instance, formulations based on synthetic polymers are made from petrochemicals, and their production processes release considerable amounts of greenhouse gases into the atmosphere, contributing to both resource depletion and climate change (Nicholson et al. 2021).

Improving soil fertility

The addition of food processing wastes and by-products to soils has the potential to improve soil fertility. Previous research has substantiated that carbohydrate- and protein-based materials can facilitate seed germination, root formation and plant development (Riseh et al. 2024; Pylak et al. 2019; Chang et al. 2015d). Food processing wastes and by-products are rich in micro- and macronutrients that are essential for plant growth and reproduction (Kumar et al. 2021). Additionally, the organic matter present in these materials can stimulate microbial activity, thereby augmenting the humification process and improving nutrient mobilization and availability (Rashid et al. 2016; Shrestha

Vaidya et al. 2008). This is particularly beneficial for revegetation and remediation efforts targeting degraded soils, such as those resulting from former mining operations.

5.2.2 Weaknesses

The term "weaknesses" refers to product features that may hinder its competitiveness in the market (Leigh 2009). In the author's opinion, the main weaknesses of using food processing wastes and by-products as dust suppressants are:

- Limited durability
- High application rates and concentrations required
- Variability in composition and dry matter content
- Organic pollution of aquatic ecosystems
- Odor emissions
- Mold infestation
- Attraction of animals
- Adverse effects on mineral processing methods

Limited durability

Dust suppressants require periodic rejuvenation to maintain their effectiveness. The durability of a product dictates the frequency of re-application and, therefore, becomes a key determinant of equipment operating costs. This factor often contributes to a significant escalation in the overall cost of dust suppressant applications and becomes more significant the longer the dust suppression effort takes (Thompson and Visser 2007; Melese et al. 2018). For this reason, for instance, traditional watering becomes exceedingly expensive in hot-dry seasons since it requires re-application nearly every two hours due to rapid evaporation (Du Plessis et al. 2016; Thompson and Visser 2002). Limited durability can also lead to an increased consumption of water.

Treatments made from food processing wastes and by-products are likely to require much shorter re-application intervals to remain effective than commercially available dust control products, such as those based on synthetic polymers. These formulations are typically marketed with a durability of 6-12 months (Piechota et al. 2004; Edwards et al. 2010). In the case of food processing wastes and by-products, this research suggests that the durability is more likely to fall within the range of days to weeks due to their inherent susceptibility to leaching by rainfall and biodegradability. This appears to be supported by the literature reviewed. For example, lignin sulphonate, which is also water soluble, biopolymer-based and biodegradable, can keep mine haul roads dust-free for up to 4 weeks (Cecala et al. 2012). However, it should be noted that a direct comparison of the durability of dust suppressants based on the literature is challenging as it depends on a number of factors, including weather and erosion conditions, dosage rate, application method and soil type (Steevens et al. 2007; Naeimi and Chu 2017).

The durability and necessary re-application intervals of water-soluble biopolymers, such as carboxymethyl cellulose or pectin, are likely comparable to those of food processing wastes and by-products. However, this does not hold true for biopolymers that only fully dissolve in heated water or in acetic or alkaline solutions, such as gellan gum, chitosan, or casein. They are expected to last longer than food processing wastes and by-products and necessitate less frequent rejuvenation because they are more resistant to rainfall and subsequent leaching. This might give a cost advantage to long-term dust control measures.

High application rates and concentrations required

The laboratory experiments of this thesis indicate that food processing wastes and by-products need to be applied at higher application rates and concentrations compared to biopolymers and commercial products to achieve similar dust suppression effectiveness. Food processing wastes and by-products, for example, decreased wind-induced soil loss by more than 99 % under laboratory conditions at concentrations and applications rates ranging between 5 % and 10 %, and 0.75 L/m² and 1.5 L/m², respectively. In comparison, biopolymers such as xanthan gum and chitosan achieved the same level of reduction at much lower concentrations of 0.1 % and application rates of 0.4 L/m² and 0.5 L/m², respectively (Kavazanjian et al. 2009). These findings are relevant as they impact the overall cost, which becomes more significant the longer the dust suppression effort takes.

Variability in composition and dry matter content

Unlike the homogeneity of commercial products, food processing wastes and by-products vary in their composition and dry matter content. Such variations may adversely affect both the solution preparation and the dust suppression effectiveness. Research conducted by Weiss and St-Pierre (2009) highlight that waste materials are prone to high levels of variability, whereas by-products tend to be moderately variable.

Organic pollution of aquatic ecosystems

As with commercial biopolymers and other organic-based dust suppressants such as lignin sulphonate, food processing wastes and by-products have the potential to increase the biochemical oxygen demand in water systems. These materials can enter surface waters and groundwater through runoff and infiltration, adding organic load to aquatic ecosystems (Singh et al. 2003; Bashir et al. 2020). The organic matter present in these materials stimulates the growth of bacteria and other microorganisms, which consume dissolved oxygen in freshwater bodies. The decrease in dissolved oxygen concentration can result in stress on aquatic life and degrade biodiversity (Vigiak et al. 2019; Ferreira et al. 2017).

Odor emissions

The use of food processing wastes and by-products as dust suppressants may give rise to strong and unpleasant odors. These odors can result from the natural smell of the material or from the microbial degradation of organic matter.

Mold infestation

Edvardsson (2009) emphasizes mold as a potential drawback of using food processing wastes and by-products as dust suppressants. Being rich in organic compounds, residues of these materials provide nutrients that can promote mold growth. Mold can proliferate on treated soil surfaces, inside application equipment or in storage tanks.

Attraction of animals

As reported by Bolander and Yamada (1999), protein- and carbohydrate-based dust suppressants, such as food processing wastes and by-products, can draw animals to application sites. Insects such as ants, beetles, and flies may be particularly attracted to these materials as they can serve as a food source. This attraction can create a cascade effect, attracting other animals such as birds, lizards, or small mammals that feed on insects.

However, whether the use of food processing wastes and by-products constitutes a strength or weakness depends on the specific stage of application within the life-of-mine cycle. Attracting animals may present operational challenges during the active mining phase, but this same characteristic becomes beneficial during mine closure and land rehabilitation, as the return of wildlife actively supports ecological restoration goals.

Adverse effects on mineral processing methods

Akin to other dust suppressants, using food processing wastes and by-products on tailings surfaces may lead to problems. The recycled water from tailings storage facilities may have significant residue concentration from these materials, which could adversely impact mineral processing methods like flotation by reacting with other chemicals involved (Park et al. 2019).

5.2.3 Opportunities

The term "opportunities" refers to external factors such as favorable situations or trends that can leverage the success of a product (Leigh 2009). In the author's opinion, the main opportunities that can drive the success of food processing wastes and by-products in the dust suppressant market are:

- Growing demand for eco-friendly dust suppression solutions
- Stricter standards for air quality
- Carbon pricing
- Increasing importance of corporate social responsibility
- Partnerships and collaborations

Growing demand for eco-friendly dust suppression solutions

The growing demand for eco-friendly dust suppression solutions presents a significant opportunity for food processing wastes and by-products to enter the market for dust control products. This trend is driven by the increasing pressure on mining companies and other industries from stakeholders including investors, local communities, and regulatory bodies to adopt sustainable practices (Dashwood 2013; Jenkins and Yakovleva 2006; Ali and O'Faircheallaigh 2005). Additionally, corporations are increasingly setting ambitious sustainability goals, aiming to minimize their environmental footprint across various aspects of operations (Hilson and Murck 2000; Fonseca et al. 2014).

Food processing wastes and by-products are well positioned to meet this demand due to their inherent eco-friendly characteristics. These materials are non-toxic and biodegradable, minimizing the risk of long-term exposure and bioaccumulation (Zumstein et al. 2022; Nair et al. 2017). They are also expected to have a significantly lower carbon footprint along their value chain than commercial dust control products and to conserve resources, as they are residuals from existing production processes rather than being intentionally created.

Stricter standards for air quality

Stricter air quality standards create an opportunity for food processing wastes and by-products to penetrate the dust suppressant market. As regulations become more stringent, the demand for effective dust control solutions is expected to rise (Kuklinska et al. 2015; Boogaard et al. 2023). Growth markets are characterized by an expanding market potential and an influx of potential buyers, many of whom lack brand loyalty

and are open to new products, such as food processing wastes and by-products (Shankar et al. 1999; Dougherty 1990).

Stricter regulations also often come with increased public and industry awareness about air quality issues, encouraging a more proactive adoption of dust suppression measures (Zhang et al. 2024b; Ji et al. 2022). This trend can further expand the market size of dust suppressants. Additionally, companies may need to apply dust suppressants more frequently or in larger quantities to comply with higher standards. This increased use can lead to a rise in the volume of product sold per customer.

Carbon pricing

In recent years, carbon pricing has emerged as a key instrument in the global transition towards a decarbonized economy (Grubb and Neuhoff 2006; Fischer and Newell 2008; Kerr 2016). This approach aims to internalize the external costs of GHG emissions, helping to capture the environmental impact of carbon-intensive activities (Goulder and Schein 2013; Klenert et al. 2018). Consequently, products and services become more expensive in proportion to their carbon footprint. This pricing mechanism presents an opportunity for food processing wastes and by-products to gain a competitive edge in the dust suppressant market. These materials typically have a significantly lower carbon footprint along their value chain compared to conventional dust control products such as those based on petroleum-based polymers, translating into a cost advantage. Looking ahead, it is reasonable to expect that carbon prices will continue to increase, further intensifying the economic benefit of using food processing wastes and by-products for dust suppression.

Increasing importance of corporate social responsibility

In recent years, corporate social responsibility (CSR) has become increasingly important within the mining industry (Slack 2012; Jenkins and Yakovleva 2006; Jenkins 2004; Mutti et al. 2012). According to Saenz (2020), a strong commitment to CSR can offer numerous benefits for companies, including increased sales and market shares, enhanced brand positioning, improved corporate image, reduced operational costs, and greater appeal to investors and financial analysts.

The growing emphasis on CSR within the mining sector presents an opportunity for food processing wastes and by-products to gain a competitive edge in the dust suppressant market. Repurposing these materials aligns with circular economy principles, demonstrating a commitment to resource efficiency and waste reduction. This approach not only minimizes waste, but also reduces the demand for virgin materials in dust suppressant production (Korhonen et al. 2018; Geissdoerfer et al. 2017; Stahel 2016; Lieder and Rashid 2016). Moreover, utilizing food processing waste for dust suppression highlights a company's innovative thinking and problem-solving capabilities, which can attract and retain partners, investors, customers and employees (Day 1994). Additionally, using food processing wastes and by-products for dust suppression is a tangible and easily communicable example of a company's environmental stewardship.

Partnerships and collaborations

Partnerships offer multifaceted opportunities for integrating food processing wastes and by-products into the dust suppressant market. For instance, collaborations among food processors, mining corporations, and universities can accelerate research

and development efforts, leading to a deeper understanding of both the potential and limitations of using these materials as dust suppressants.

Partnerships not only enhance credibility but also boost market awareness. Collaborating with reputable companies and academic institutions lends credibility and helps to gain market trust (Todeva et al. 2005; Varadarajan and Cunningham 1995). Endorsements from well-known organizations often builds potential customers' confidence, increasing their willingness to adopt innovative solutions and products, such as using food processing wastes and by-products for dust suppression (Dean and Biswas 2001).

Moreover, these collaborations offer food processors with access to a new customer base. Mining companies and service providers represent new market opportunities that are typically outside the food industry's sphere of influence. Partnerships can open up new avenues for business expansion, facilitating engagement with mining operations of various scales across diverse geographical locations. This geographical and market diversification offers broader economic opportunities for food processing companies.

5.2.4 Threats

The term "threats" refers to external factors that can harm the success of a product (Leigh 2009). In the author's opinion, the main threats that can hinder the success of food processing wastes and by-products in the dust suppressant market are:

- Competing environmentally friendly dust suppression options
- Competition with other forms of utilization
- Limited market awareness
- Changes in the landscape of the food processing industry
- Low-availability periods
- Employee complaints and resistance

Competing environmentally friendly dust suppression options

The growing environmental awareness will lead to an increased demand for eco-friendly dust suppression solutions. Food processing wastes and by-products, along with alternatives like biopolymers, MICP and EICP, cater to this market, placing them in direct competition with one another. Simultaneously, commercial product manufacturers are also expanding their presence in this segment. However, this competition poses several challenges for introducing food processing wastes and by-products as dust suppressants. For example, mining companies and service providers often have existing contracts with other manufacturers and preferences for specific dust control products, creating barriers for new market participants. Furthermore, existing competing options have been subject to extensive research, potentially giving them an edge in product development and optimization. Additionally, competitors with substantial research funding or corporate support can further threaten new market participants by leveraging their financial resources to accelerate the development, market penetration and acceptance of their products. Moreover, commercial manufacturers of dust control products have better market awareness and established distribution channels, making it easier for them to expand their market share.

Competition with other forms of utilization

Wastes and by-products from food processing can be valorized in a variety of ways, from animal feed to raw materials for biofuels (Chandrasekaran 2012). Moreover, these materials can serve as valuable resources for producing nutrient-rich compost for agriculture and horticulture. The extraction of high-value compounds such as pectin and antioxidants from certain food processing wastes and by-products further expands their industrial applications (Ribeiro et al. 2022).

However, this multi-sectoral demand creates competitive challenges. Increased demand across industries may limit the availability of food processing wastes and by-products for dust suppression applications. This may be intensified by existing relationships between food processors and established customers, which are likely to secure preferential access to these materials. Growing competition can also lead to price fluctuations, potentially affecting the economic viability of using these materials as dust suppressants (Inderst 2002). Moreover, novel applications face challenges in penetrating the existing market and gaining acceptance from stakeholders (Wüstenhagen et al. 2007).

Limited market awareness

A lack of market awareness threatens the market adoption of food processing wastes and by-products as dust suppressants. Potential customers are unlikely to consider these materials as an option if they are unaware of their existence and capability for dust suppression.

Furthermore, old, established industries, particularly mining, are often resistant to change and introducing innovative, unfamiliar solutions. Without knowledge of the benefits, they will continue their current practices, despite the new products being more environmentally friendly or cost-effective. Creating awareness through case studies, testimonials and data-driven evidence is therefore critical to overcoming barriers to adopting and driving the success of these environmentally friendly alternatives in the dust suppressant market.

Changes in the landscape of the food processing industry

Changes in the landscape of the food processing industry can have a direct impact on the availability and supply of wastes and by-products suitable for use as dust suppressants. Shifts in consumer demand or preferences for certain food products can lead to changes in types and quantities of raw materials processed by the food industry. This, in turn, may change the composition, volume and types of wastes and by-products generated during processing operations. Moreover, introducing new food products or adopting new market trends can cause food processors to modify their production lines or processing methods (Gehlhar and Regmi 2005; Buttriss 2013). Advances in food processing technologies can also affect the efficiency of the production process and the nature of the wastes and by-products generated. In addition, changes in regulations relating to food safety, environmental protection or waste management may require the food processing industry to modify its operations or adopt new practices (King et al. 2017; Trienekens and Zuurbier 2008).

Low-availability periods

Low-availability periods can pose challenges for companies relying on food processing wastes and by-products for dust suppression. Crop yields can fluctuate from year to year due to weather conditions, pests, or changes in agricultural practice (Liliane

and Charles 2020). Moreover, many agricultural products are harvested at specific times of the year, leading to an uneven production of food processing wastes and by-products throughout the year. In this context, however, it is important to note that food processing wastes and by-products generally have a shelf life that allows them to be stored for several months to years (safety data sheets; available on the supplied SD card).

Complaints and resistance from employees

Applying food processing wastes and by-products as dust suppressants potentially result in odor emissions, attracting animals, or promoting mold growth (Section 5.3.2). Such nuisances may cause employees to complain or resist the use of these materials for dust suppression. Appropriate mitigation techniques should be implemented to address these concerns.

5.2.5 Conclusions

The SWOT analysis reveals a promising potential for food processing wastes and by-products to compete in the dust suppressant market. Key strengths of these materials include biodegradability, resource conservation and a reduced carbon footprint. Their ability to be handled, stored, prepared and applied easily, coupled with exceptionally competitive pricing, positions them as attractive alternatives to both conventional and green emerging dust control solutions.

However, these strengths are balanced by certain drawbacks, such as limited durability, high dosage rates and compositional variability. Additionally, the potential for organic pollution in aquatic systems warrants careful consideration and mitigation strategies. Despite these weaknesses, using food processing wastes and by-products for dust suppression can offer significant benefits in terms of environmental friendliness, cost-effectiveness and ease of use.

The growing emphasis on sustainability from corporations and their stakeholders creates a favorable climate for the market entry and adoption of food processing wastes and by-products as dust suppressants. However, competition with other forms of utilization and eco-friendly dust control options as well as changes in the landscape of the food processing industry pose notable threats. Its success will depend on effectively communicating the unique selling points of food processing wastes and by-products and building awareness among potential buyers. By strategically leveraging their strengths and opportunities while mitigating weaknesses and threats, food processing wastes and by-products can carve out a niche in the dust suppressant market.

5.3 Implications

The thesis findings have numerous theoretical and practical implications.

5.3.1 Theory

This work has uncovered the untapped potential of utilizing food processing wastes and by-products as environmentally friendly dust suppressants. Through experimentation, it was discovered that a diverse range of these materials have the potential to be applied as dust suppressants. Notably, many of the materials studied have yet to be evaluated for their dust suppression effectiveness, rendering this research a pioneering effort.

This thesis demonstrates that aqueous solutions of carbohydrate- and protein-rich materials can effectively reduce wind-induced dust emissions for short-term peri-

ods (< 28 days) under actual environmental conditions. Gathering such field data is important given the need for research on the durability and reliability of biomaterials, like biopolymers, in geotechnical applications (e.g., dust suppression and wind erosion control) in real-world settings, as emphasized by Chang et al. (2020). Hence, this work makes a valuable contribution to our understanding of how water-soluble, biodegradable materials can function as dust suppressants, how environmental factors can influence their effectiveness over time and at what application rates and concentrations they are effective. These insights can aid in comprehending the mechanisms by which such reagents interact with soil particles and the environment. Ultimately, the findings of this research contribute to the development of more efficient and environmentally conscious dust suppression strategies for a range of applications (see Section 5.4.2).

The current work reveals that soil plots eroded with commercially available electric blowers pose an effective method for evaluating the performance of reagents in suppressing wind-induced dust emissions in the field. Such an experimental setup offers numerous benefits compared to the conventional method of quantifying dust emissions from soils via field boundary layer wind tunnels, which can be cumbersome to transport, time-consuming, and present methodological difficulties, as reported by Kavouras et al. (2012) and McKenna Neuman et al. (2009). In contrast, the experimental setup described in this thesis is characterized by its cost-effectiveness, ease of use and practicality, made possible by readily accessible equipment. This setup permits testing numerous dust suppressants with replicates at various intervals and locations where they are intended to be applied. By facilitating the collection of robust field data, the experimental setup helps address the lack of information on dust suppressant effectiveness on surfaces susceptible to wind erosion under real environmental conditions, as previously acknowledged by Katra (2019).

The laboratory wind erosion and field experiments demonstrated that food processing wastes and by-products can create erosion-resistant soil surfaces and prevent the release of particulates into the atmosphere. These findings emphasize the utility of the UCS test as a reliable screening method for assessing the wind erosion control and dust suppression potential of materials, which was carried out prior to the tests.

The results of this research could potentially stimulate further investigation and development in the field of eco-friendly dust suppressants. For instance, follow-up studies could compare the effectiveness, durability, cost-efficiency, or environmental impact of food processing wastes and by-products against traditional and other biodegradable dust suppressants to establish their viability as sustainable dust suppression solutions. Alternatively, the research approach presented in this thesis could be replicated in different geographic regions or on different types of mine soil.

The thesis experiments also suggest that mono- and disaccharide-based materials can be effectively applied as dust suppressants. These results may challenge the current emphasis on biopolymers, EICP, and MICP for environmentally friendly dust suppression.

The thesis holds implications for a broader scientific community within the field of geotechnical engineering. UCS experiments showed significant improvements in the compressive strength of sand reinforced with food processing wastes and by-products. In part, the UCS values obtained were comparable to those reported in the literature for biopolymers (cf. Figure 3-3 and Table 3-5). Based on UCS test data, previous studies

showed that biopolymers are effective agents for ground improvement (Chang and Cho 2012; Chang et al. 2015c; Chang et al. 2017; Nair and Kannan 2020). Thus, the current work provides initial evidence that wastes and by-products from food processing can also potentially act as soil stabilizers. These findings hold promise for current efforts to identify more sustainable solutions for enhancing soil strength (Soldo et al. 2020). Traditionally, soil strength was increased using stabilizers such as cement, lime and fly ash (Karol 2003; Fatehi et al. 2021). However, these agents are often costly or have negative environmental impacts, such as increasing pH value and decreasing soil fertility (Md Zahri and Zainorabidin 2019).

The thesis findings can also be relevant for researchers interested in soil conservation. Laboratory-based wind tunnel and field experiments showed that food processing wastes and by-products can effectively reduce wind-induced soil loss, thus presenting a promising solution for wind erosion control. Potential areas of application include croplands, drylands, dunes and planting initiatives, such as reforestation after wildfires, reclamation of mined land or revegetation after earthworks. Applying food processing wastes and by-products can stabilize soil particles and seeds against erosive forces while supporting seed germination and plant growth (Riseh et al. 2024; Ni et al. 2024).

5.3.2 Practice

This work provides empirical evidence supporting the potential of food processing wastes and by-products to be used as dust suppressants. Such research can raise awareness of sustainable dust control practices and promote their adoption.

There are numerous potential applications in mining where wastes and by-products from food processing can be used as dust suppressants. Firstly, these materials can be applied to control wind-blown dust from barren mine soils. Wind-sensitive surfaces are typical for slopes, berms, tailings pond beaches, waste heaps or overburden dumps. Secondly, treating pulverized minerals with food processing wastes and by-products can prevent their loss during stockpile storage, transportation (e.g., open-top hopper rail cars) and while waiting in port. Eventually, there is also the potential to use them for dust control on unpaved surfaces exposed to occasional or channelized traffic, such as benches and haul roads. However, it is assumed that the durability of dust suppression treatments made from food processing wastes and by-products is likely to be shorter in such areas of operations than to those solely susceptible to wind erosion.

Dust control extends beyond mining and plays a significant role in other industries such as agriculture, construction, forestry, and military operations. This opens up a wide range of other possible applications in which food processing wastes and by-products can be used as dust suppressants. In agriculture, food processing wastes and by-products can be applied to control dust from croplands and on areas that are not arable, yet integral to farm operations, such as dirt roads, equipment yards and drainage/irrigation system infrastructure (Arslan and Aybek 2012). This application helps maintain air quality and reduces the loss of fertile soil in agricultural settings. On construction sites, food processing wastes and by-products can be used to mitigate dust from trucks traveling on unpaved roads and fines stockpiles exposed to wind action. Once earthworks are complete, food processing wastes and by-products can also be applied to stabilize soil surfaces during revegetation efforts. In forestry, food processing wastes and by-products may be suitable for dust control on forest roads and soil erosion control

after wildfires (Vega et al. 2014). Their application can stabilize soil and seed against wind erosion until a vegetation cover is established. In military settings, food processing wastes and by-products can be used to prevent wind erosion on training sites. Training activities with wheeled and tracked military vehicles decrease vegetation cover, destroy biological crusts and cause soil degradation (van Donk et al. 2003). Such disturbed lands exhibit increased erodibility and can emit substantial amounts of wind-blown dust (Meeks et al. 2014). Other applications include controlling dust emissions from unpaved roads and preparing helipads on bare ground (Orts et al. 2007).

Compared to conventional dust suppressants (e.g., water, organic petroleum-based products, or synthetic polymer emulsions), wastes and by-products from food processing can suppress dust emissions in a more environmentally friendly manner. These materials are non-toxic, degrade naturally in the environment, require less water, and exhibit lower carbon footprints. Hence, the thesis findings can contribute to mitigating the environmental impacts of dust suppression measures, leading to a more sustainable extraction of raw materials.

In comparison to biopolymers, such as EICP and MICP, food processing wastes and by-products have the potential to be a more cost-effective and easy-to-use option for environmentally friendly dust suppression. Food processing wastes and by-products are readily available, have significantly lower product prices and can be sourced regionally, helping companies decrease the overall cost of dust control, rendering particularly short-term dust control efforts inexpensive. Additionally, these materials are readily dissolvable in cold water and do not impair rheology, implying effortless solution preparation and application with standard equipment such as water carts. Hence, the thesis findings can make a contribution towards reducing the financial and practical barriers to implementing environmentally friendly dust control measures.

By implementing sustainable practices, such as reusing food processing wastes and by-products for dust suppression, companies can enhance their corporate image and legitimacy (Quintana-García et al. 2022; Truong et al. 2021; Amores-Salvadó et al. 2014). In polluting sectors such as mining, demonstrating a commitment to environmental responsibility can help obtain and maintain the social license to operate (SLO). The SLO reflects the acceptance of a project or company by its stakeholders, including employees, local communities and authorities. Securing sufficient social approval is considered essential for the long-term viability of any mining activity (Bice et al. 2017; Lacey and Lamont 2014; Komnitsas 2020).

This research also supports the trend towards zero-waste processes in the food industry, which involves repurposing waste materials to create new, high-value products and applications (Ribeiro et al. 2022; Torres-León et al. 2018; Garcia-Garcia et al. 2019). By utilizing food processing wastes and by-products for dust suppression, producers may not only reduce the amount of waste that needs to be disposed of and the associated costs but also diversify their revenue streams and potentially generate new sources of income. This aligns with the industry's goals of turning waste into a valuable resource, maximizing efficiency, and minimizing negative environmental impact (Garcia-Garcia et al. 2019; Ravindran and Jaiswal 2016; Donner et al. 2020). Hence, the thesis findings can help the food industry close the loop and move towards a more circular economy.

5.4 Recommendations for Future Work

Further research is necessary to fully understand the limitations and potential of food processing wastes and by-products as dust suppressants. The following recommendations and suggestions outline possible directions for future work:

- Investigate the effectiveness and durability under a range of ambient conditions, over different time horizons, at locations where they are intended to be applied, and on different mine soils with varying levels of fines content, mineral composition and organic matter.
- Carry out experiments in an environmental chamber to investigate the effects of environmental exposure on effectiveness and to understand the mechanisms of degradation.
- Perform experiments simulating traffic conditions to assess the effectiveness and durability on travel surfaces.
- Conduct field studies at various application rates and concentrations to identify the optimal dosage rate to balance effectiveness and durability with cost-efficiency.
- Determine the frequency of re-application required to maintain a specified level of dust suppression.
- Explore how the method of application (i.e., topical spraying or incorporation into the ground) impacts effectiveness, durability and cost.
- Quantify the cost of establishment and re-application and identify the major cost drivers.
- Undertake biodegradability tests, toxicity tests, soil quality tests, water quality tests, etc. to assess potential effects on plants, animals and ecosystems and identify any potential risks.
- Analyze the carbon and water footprint.
- Compare the effectiveness, durability, cost and potential environmental impacts with both conventional dust suppressants and other eco-friendly alternatives (e.g., biopolymers, EICP, and MICP) currently being discussed in research.

5.5 A Final Word

In closing, it is imperative to stress that the current body of research surrounding environmental-friendly reagents for dust suppression relies heavily on laboratory trials with a range of experimental setups, making it challenging to compare and assess the data accurately. Thus, it is vital to establish standardized testing procedures and prioritize field experiments in future research efforts. By doing so, we can more accurately comprehend the potential and limitations of these materials and identify the most effective and sustainable approaches for dust suppression.

Appendix A
Statistical Analysis and Visualizations of Compaction and UCS Test Results

Appendix A summarizes the UCS test data presented in Chapter 2 and provides compaction and stress-strain curves, serving as visual aids to supplement the quantitative data.

A.1 Statistical Analysis

Table A-1. Statistical summary of UCS test data.

Substance	UCS (kPa)									
	Additive concentration (wt%)									
	2					4				
	Parameter									
	R-1	R-2	R-3	M	SD	R-1	R-2	R-3	M	SD
AM	296.7	451.6	408.1	385.4	79.9	59.1	42.2	39.9	47.1	10.5
BM	79.8	39.8	17.2	45.6	31.7	86.9	161.7	69.8	106.1	48.9
BV	283.0	201.3	191.6	225.3	50.2	13.1	12.9	11.3	12.4	1.0
CM	194.3	285.0	322.9	267.4	66.1	259.1	282.0	218.4	253.2	32.2
CV	1896.1	1889.2	1382.6	1722.6	294.5	989.2	938.9	1185.9	1038.0	130.6
CDS	490.0	415.9	466.3	457.4	37.8	N/A [a]	N/A [a]	N/A [a]	N/A [a]	N/A [a]
CSL	1524.4	1598.5	1383.1	1502.0	109.4	N/A [a]	N/A [a]	N/A [a]	N/A [a]	N/A [a]
DS	1977.6	2121.2	2381.9	2025.5	82.9	1909.5	1718.8	1469.1	1699.2	220.9
DWC	672.5	1220.6	1217.3	1036.8	315.5	2821.5	414.7	367.5	1201.2	1403.4
DG	174.9	164.4	142.3	160.6	16.6	15.5	12.3	16.4	14.8	2.2
FC	486.9	464.3	444.8	465.4	21.1	933.3	1480.4	1225.1	1212.9	273.7
GSR	11.7	12.7	20.3	14.9	4.7	N/A [a]	N/A [a]	N/A [a]	N/A [a]	N/A [a]

Continued on next page…

Table A-1. *Continued from previous page.*

Substance	UCS (kPa)									
	Additive concentration (wt%)									
	2					4				
	Parameter									
	R-1	R-2	R-3	M	SD	R-1	R-2	R-3	M	SD
MPP	149.3	169.8	103.5	140.9	34.0	498.0	697.4	632.7	609.4	101.8
PAM	2271.6	1705.5	1778.0	1918.4	308.0	7927.6	7065.7	7612.3	7535.2	436.1
RWJP	1188.1	1236.1	1675.0	1366.4	268.4	N/A [a]	N/A [a]	N/A [a]	N/A [a]	N/A [a]
WPP	95.8	131.6	136.0	121.1	22.1	448.5	237.4	295.7	327.2	109.0

Note. Abbreviations: AM = Apple Molasses, BM = Beet Molasses, BV = Beet Vinasses, CM = Chicory Molasses, CV = Chicory Vinasses, CDS = Concentrated Distillers Solubles, CSL = Corn Steep Liquor, DS = Decantation Syrup, DWC = Deproteinized Whey Concentrate, DG = Dextrose Greens, FC = Filter Concentrate, GSR = Glucose Syrup Retentate, M = Mean, MPP = Milk Permeate Powder, N/A = Not Available, PAM = Palatinose Molasses, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, RWJP = Rinsing Water from Jam Production, SD = Standard Deviation, UCS = Unconfined Compressive Strength, WPP = Whey Permeate Powder.

[a] Samples were only prepared at an additive concentration of 2 wt% (by dry soil weight) due to the low dry matter content of the material.

A.2 Standard Proctor Compaction Curves

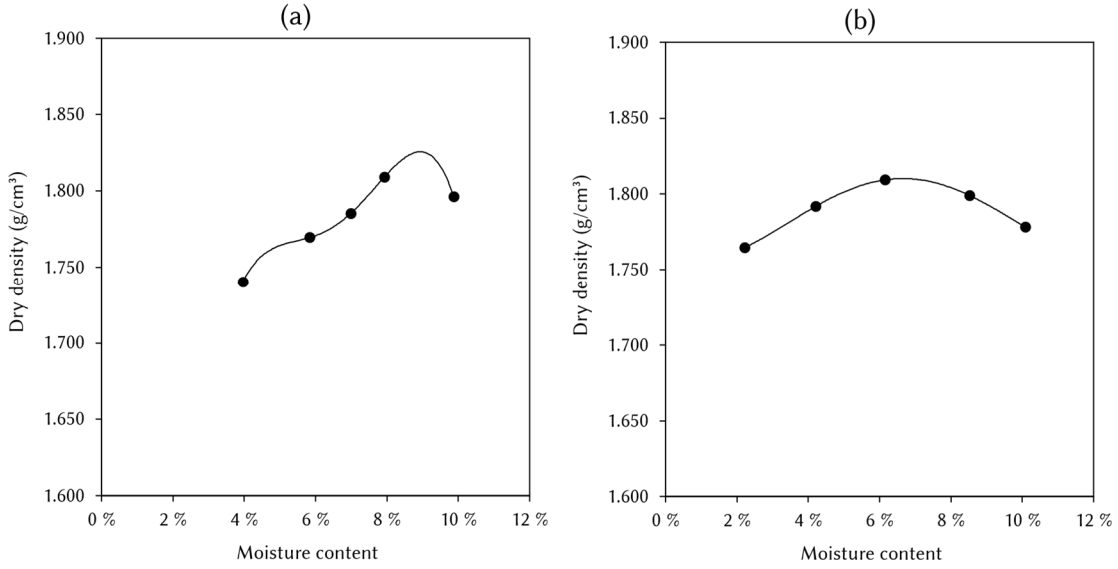


Figure A-1. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% apple molasses, and **(b)** 4 wt% apple molasses.

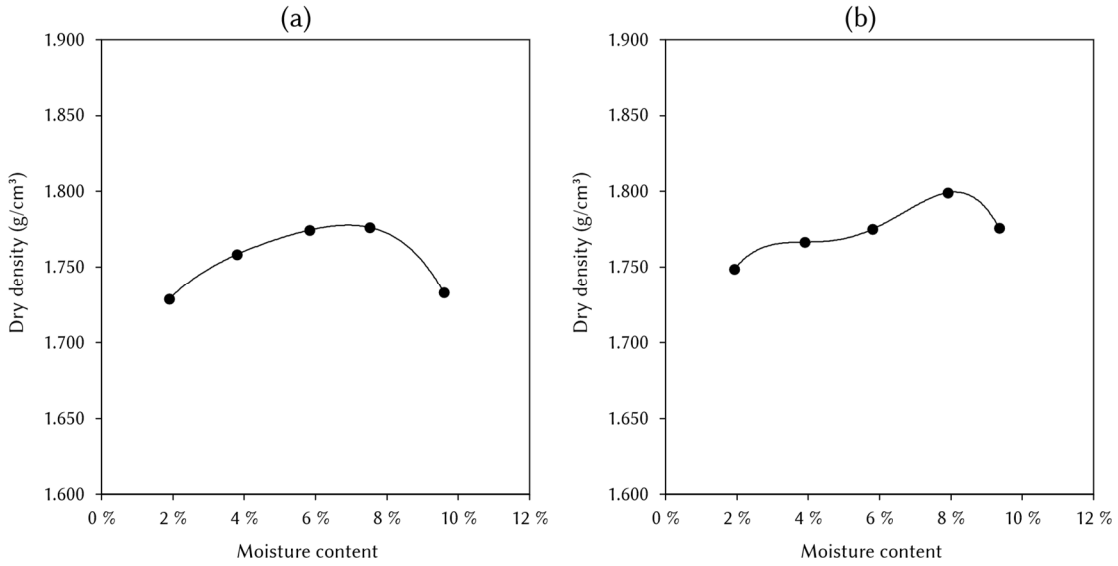


Figure A-2. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% beet molasses, and **(b)** 4 wt% beet molasses.

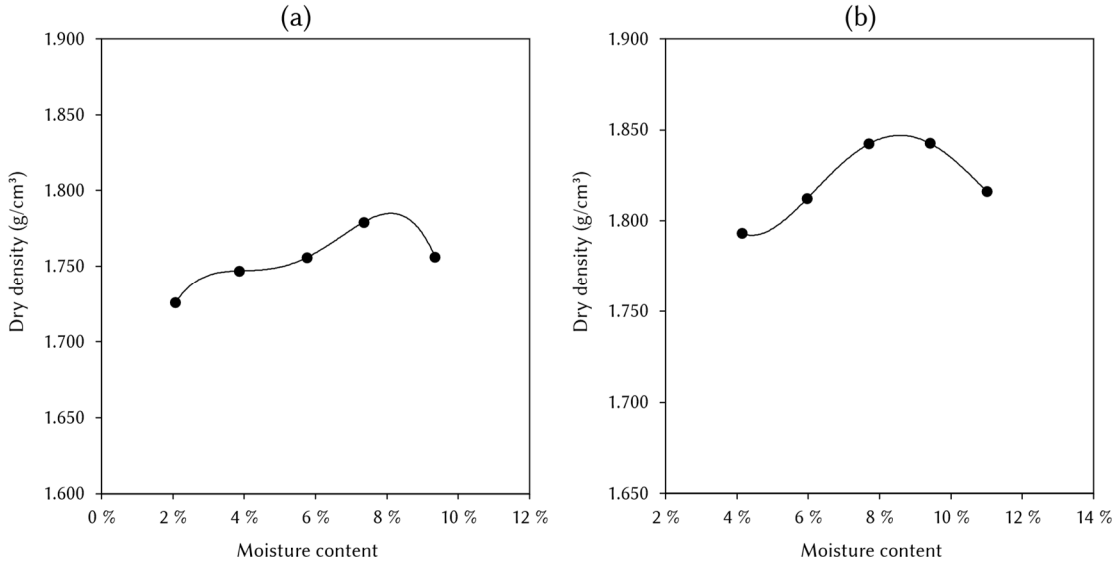


Figure A-3. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% beet vinasses, and **(b)** 4 wt% beet vinasses.

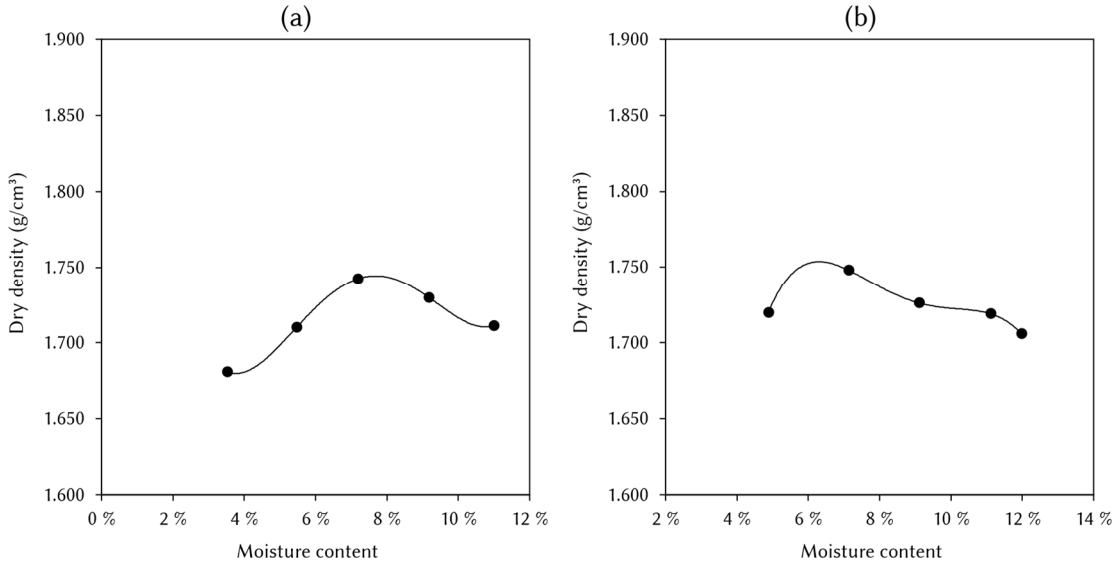


Figure A-4. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% chicory molasses, and **(b)** 4 wt% chicory molasses.

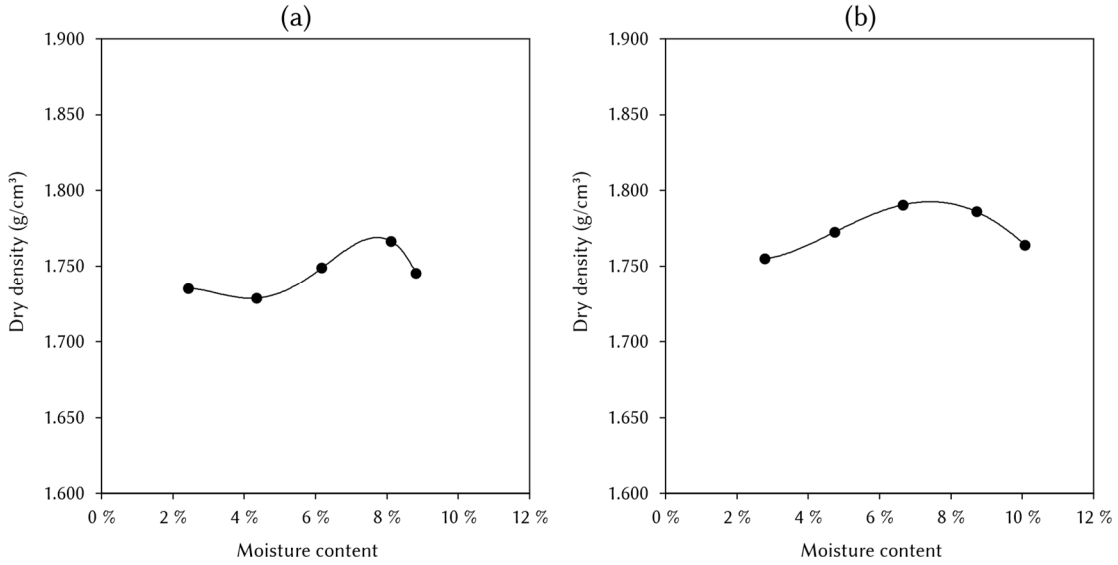


Figure A-5. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% chicory vinasses, and **(b)** 4 wt% chicory vinasses.

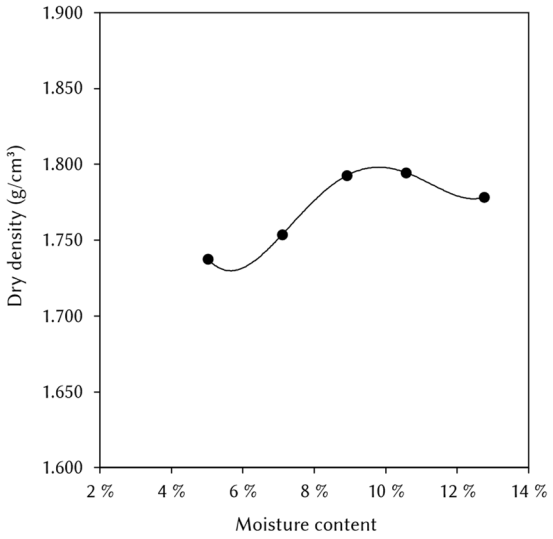


Figure A-6. Standard Proctor compaction curves of sand treated with 2 wt% concentrated distillers solubles.

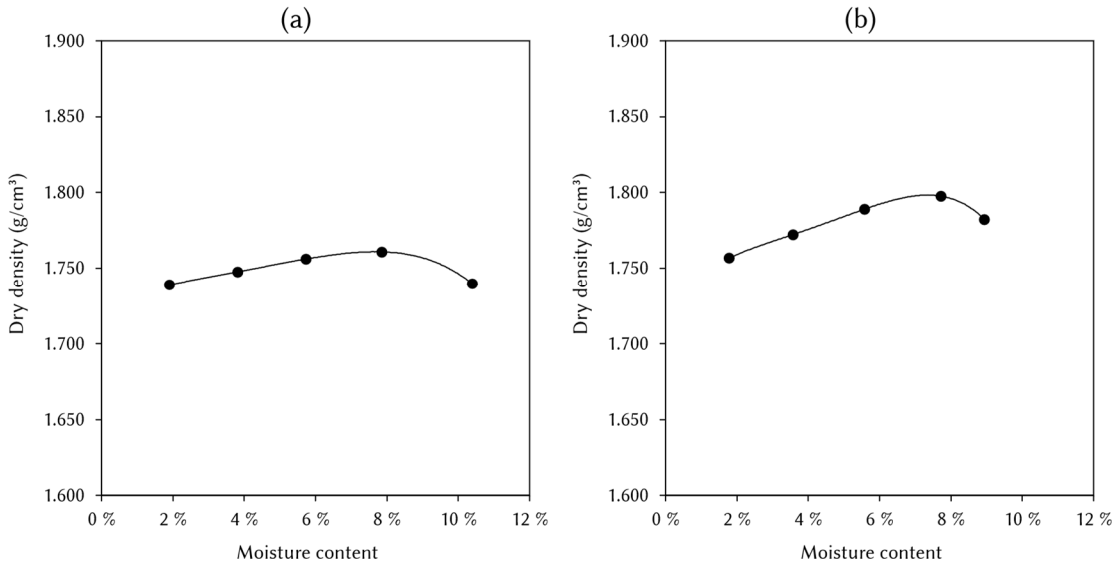


Figure A-7. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% decantation syrup, and **(b)** 4 wt% decantation syrup.

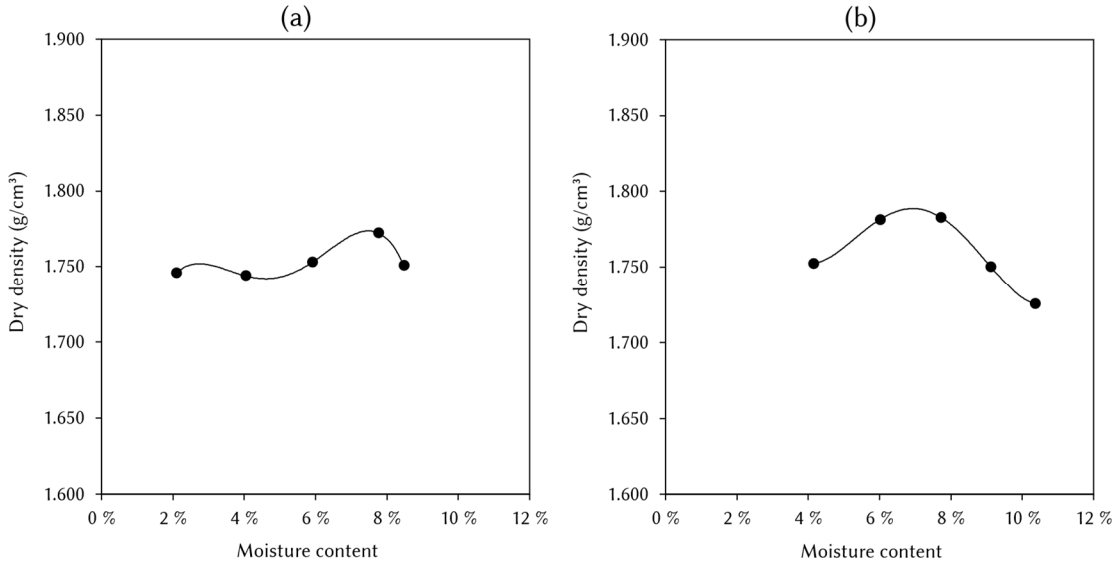


Figure A-8. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% deproteinized whey concentrate, and **(b)** 4 wt% deproteinized whey concentrate.

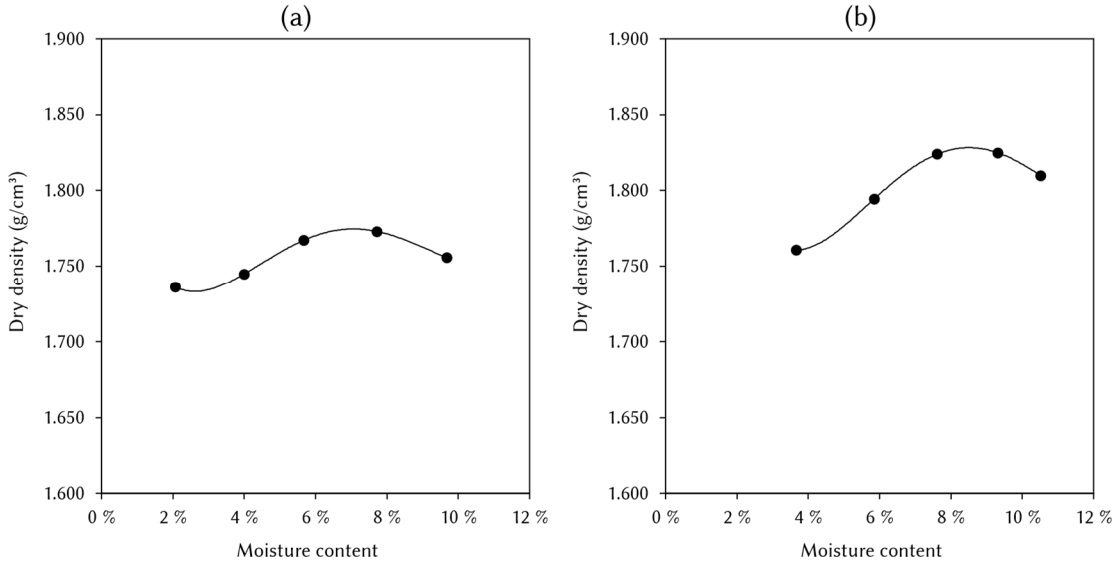


Figure A-9. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% dextrose greens, and **(b)** 4 wt% dextrose greens.

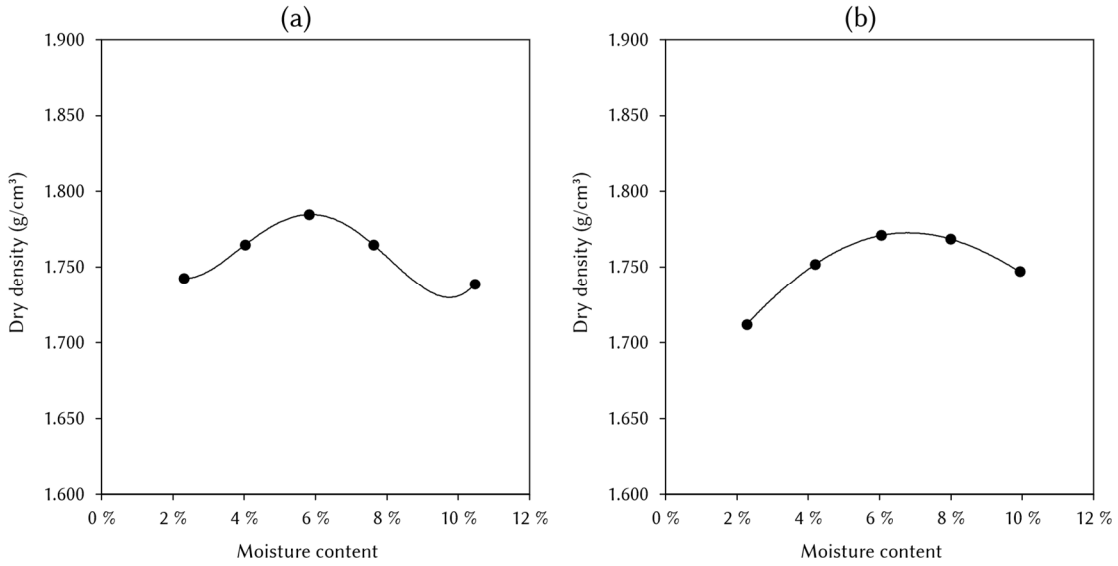


Figure A-10. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% filter concentrate, and **(b)** 4 wt% filter concentrate.

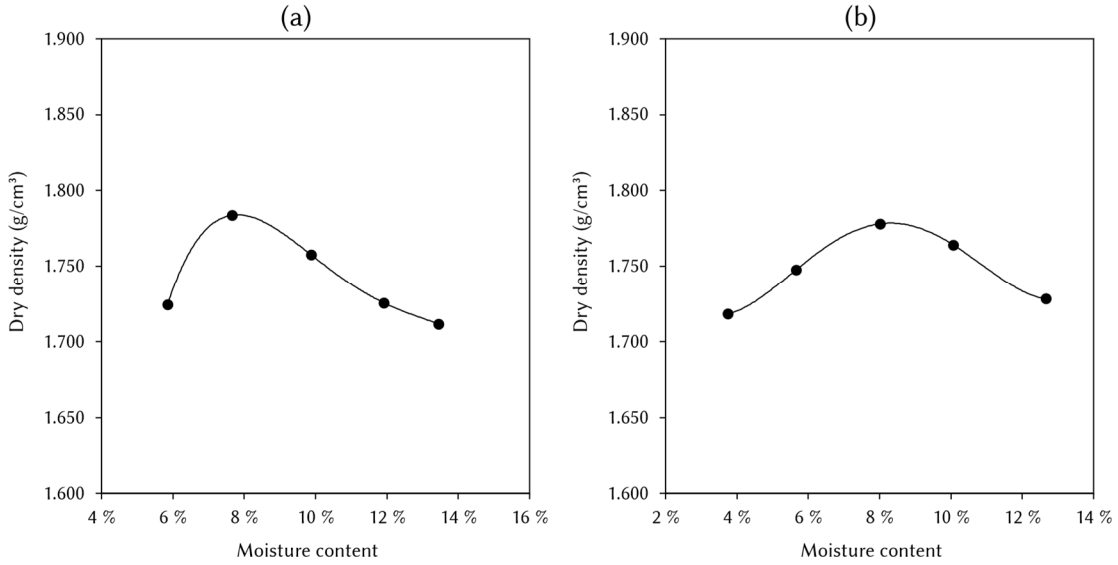


Figure A-11. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% glucose syrup retentate, and **(b)** 2 wt% rinsing water from jam production.

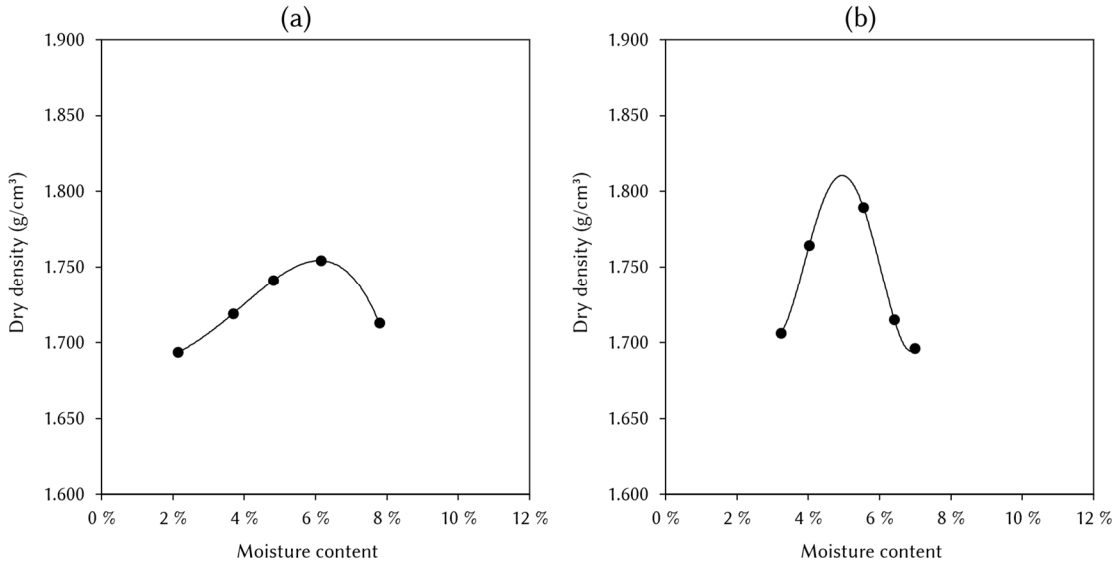


Figure A-12. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% milk permeate powder, and **(b)** 4 wt% milk permeate powder.

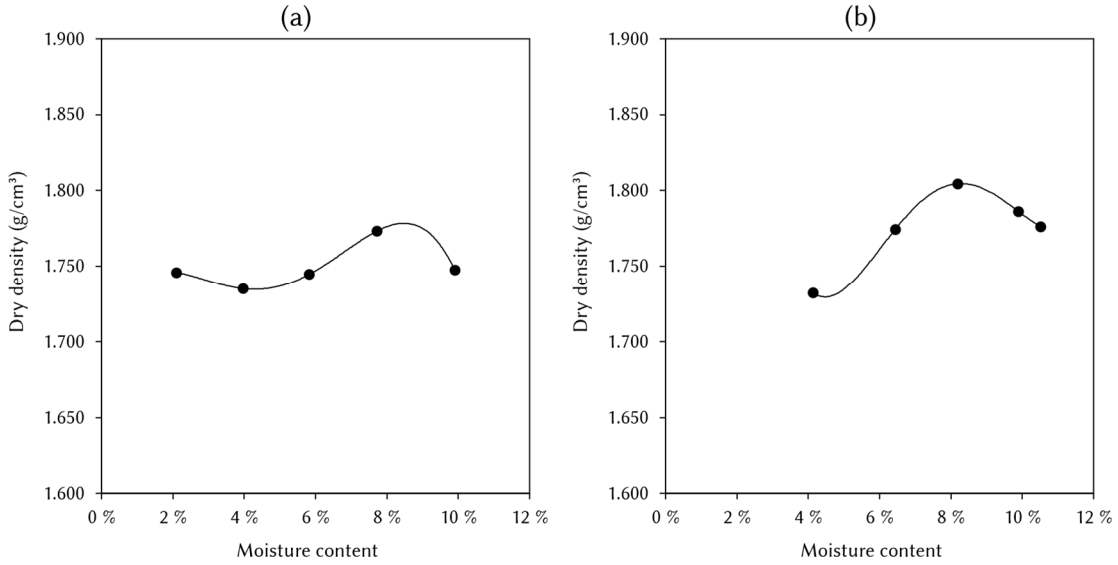


Figure A-13. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% palatinose molasses, and **(b)** 4 wt% palatinose molasses.

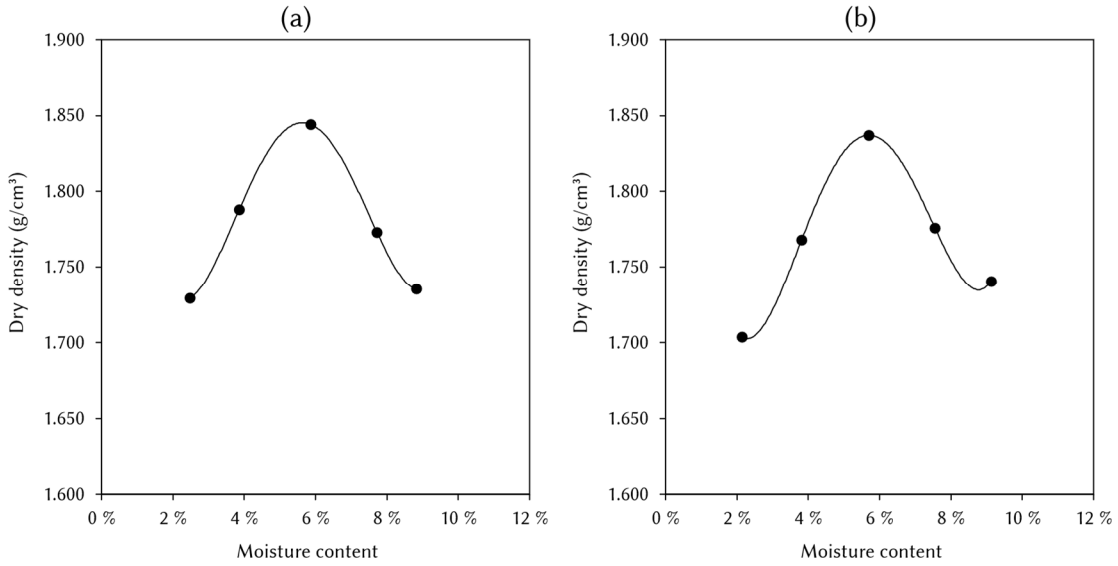


Figure A-14. Standard Proctor compaction curves of sand treated with: **(a)** 2 wt% whey permeate powder, and **(b)** 4 wt% whey permeate powder.

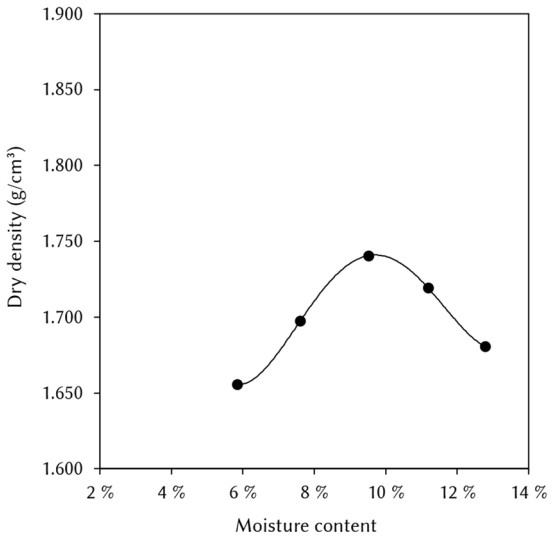


Figure A-15. Standard Proctor compaction curve of untreated sand.

A.3 Stress-Strain Curves

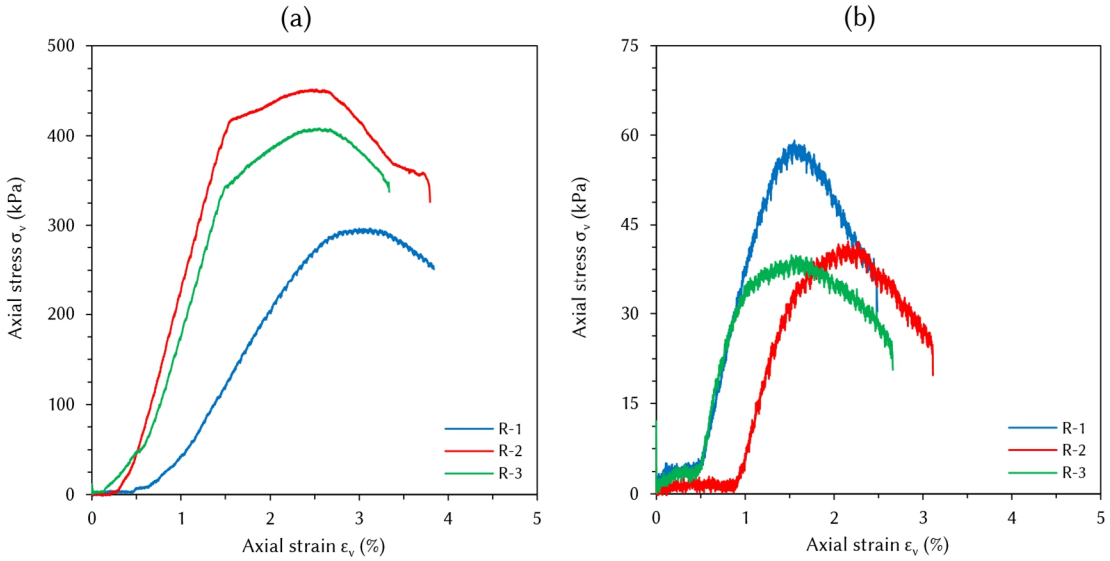


Figure A-16. Stress-strain curves of sand treated with: **(a)** 2 wt% apple molasses, and **(b)** 4 wt% apple molasses. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

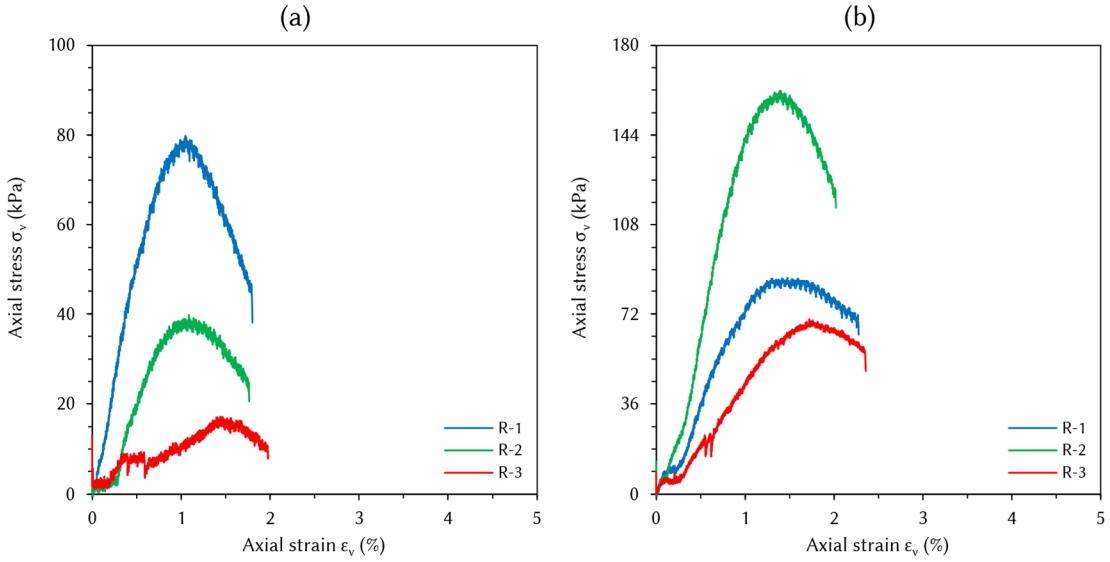


Figure A-17. Stress-strain curves of sand treated with: **(a)** 2 wt% beet molasses, and **(b)** 4 wt% beet molasses. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

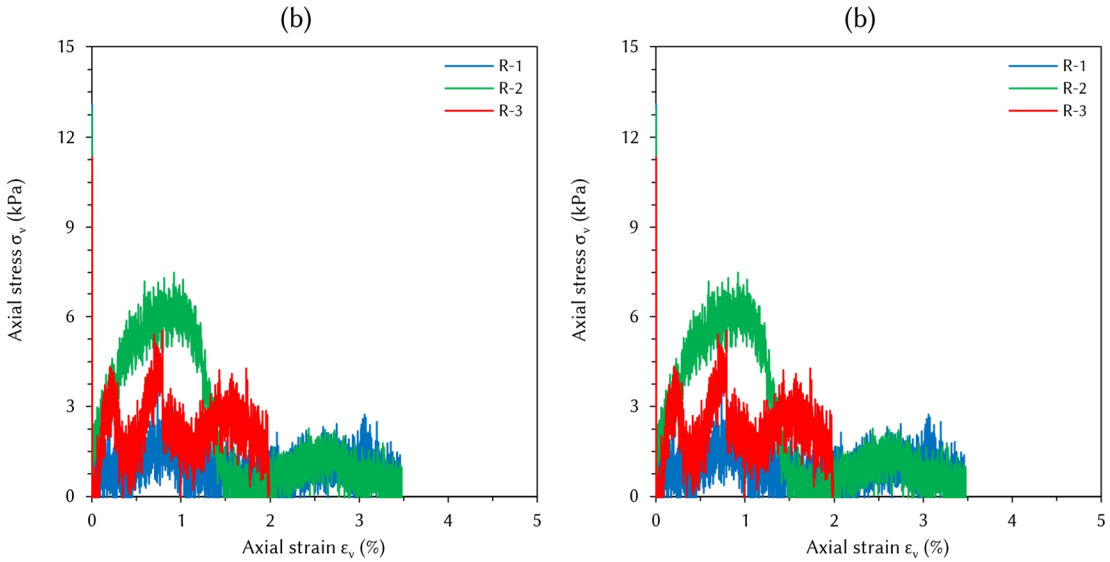


Figure A-18. Stress-strain curves of sand treated with: **(a)** 2 wt% beet vinasses, and **(b)** 4 wt% beet vinasses. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

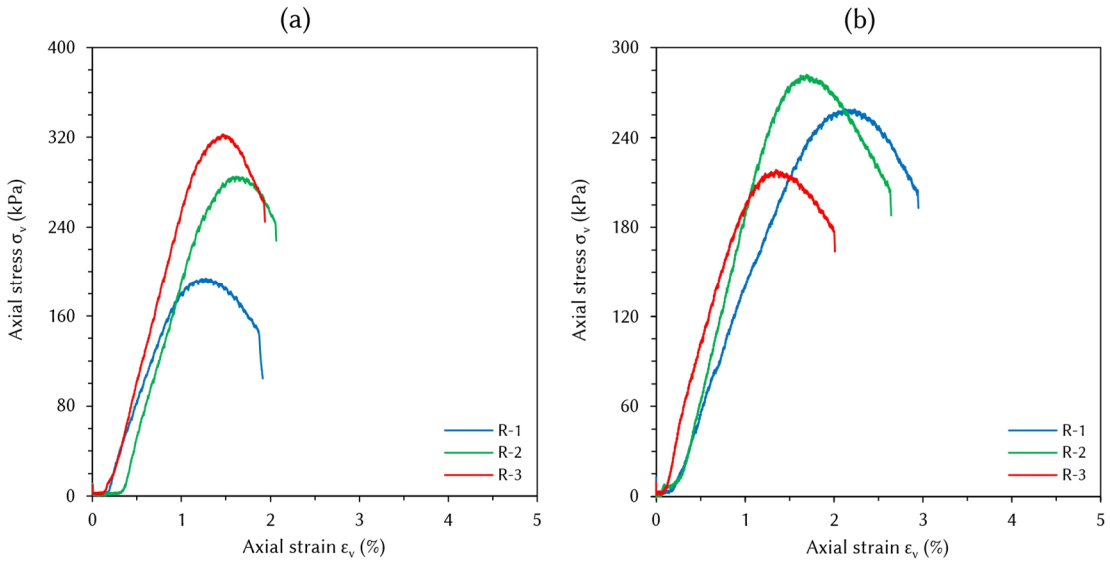


Figure A-19. Stress-strain curves of sand treated with: **(a)** 2 wt% chicory molasses, and **(b)** 4 wt% chicory molasses. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

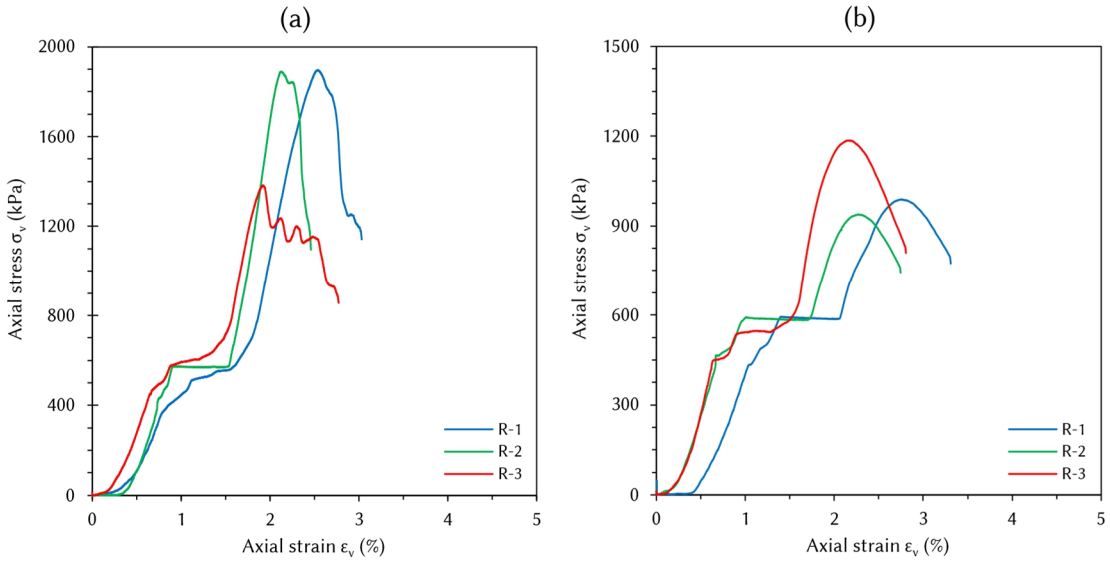


Figure A-20. Stress-strain curves of sand treated with: **(a)** 2 wt% chicory vinasses, and **(b)** 4 wt% chicory vinasses. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

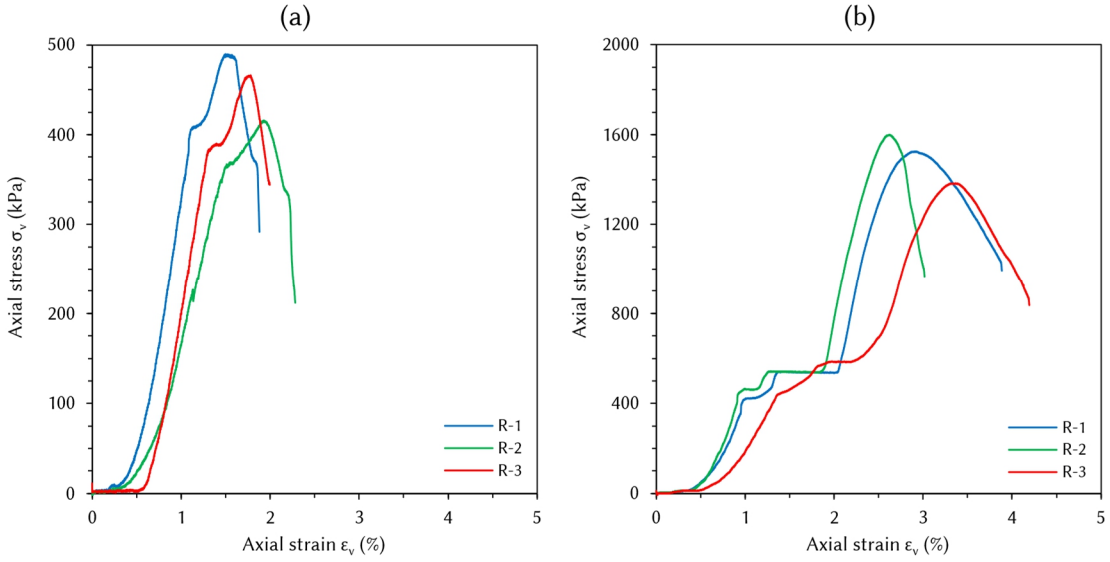


Figure A-21. Stress-strain curves of sand treated with: **(a)** 2 wt% concentrated distillers solubles, and **(b)** 2 wt% corn steep liquor. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

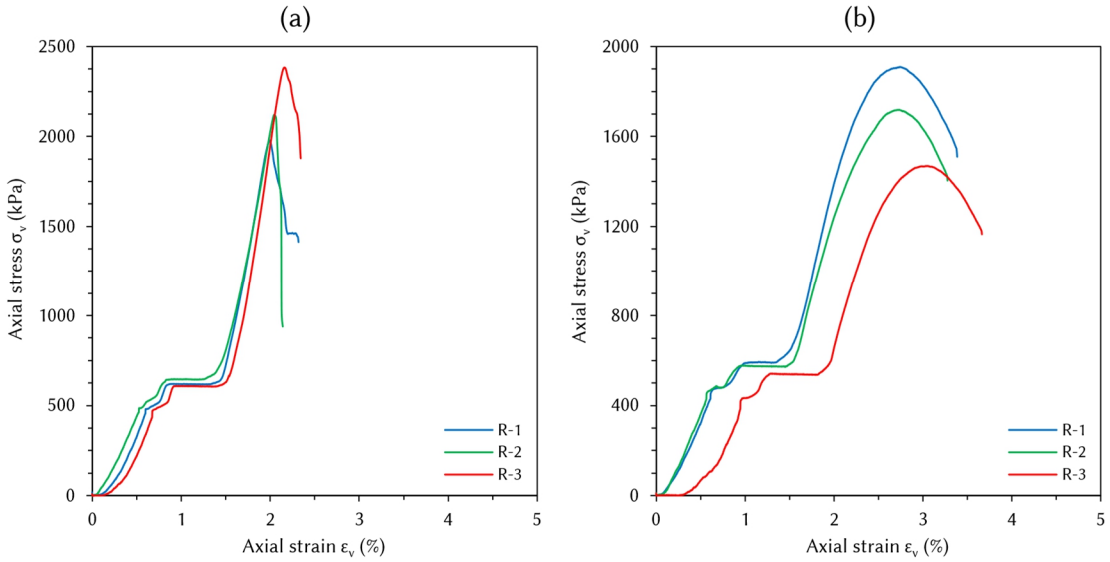


Figure A-22. Stress-strain curves of sand treated with: **(a)** 2 wt% decantation syrup, and **(b)** 4 wt% decantation syrup. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

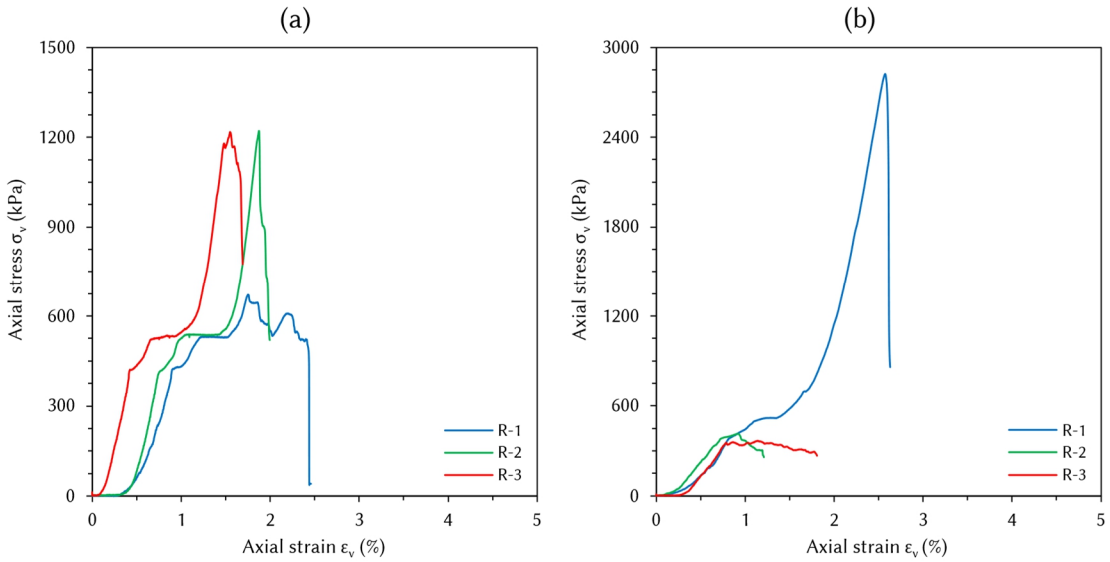


Figure A-23. Stress-strain curves of sand treated with: **(a)** 2 wt% deproteinized whey concentrate, and **(b)** 4 wt% deproteinized whey concentrate. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

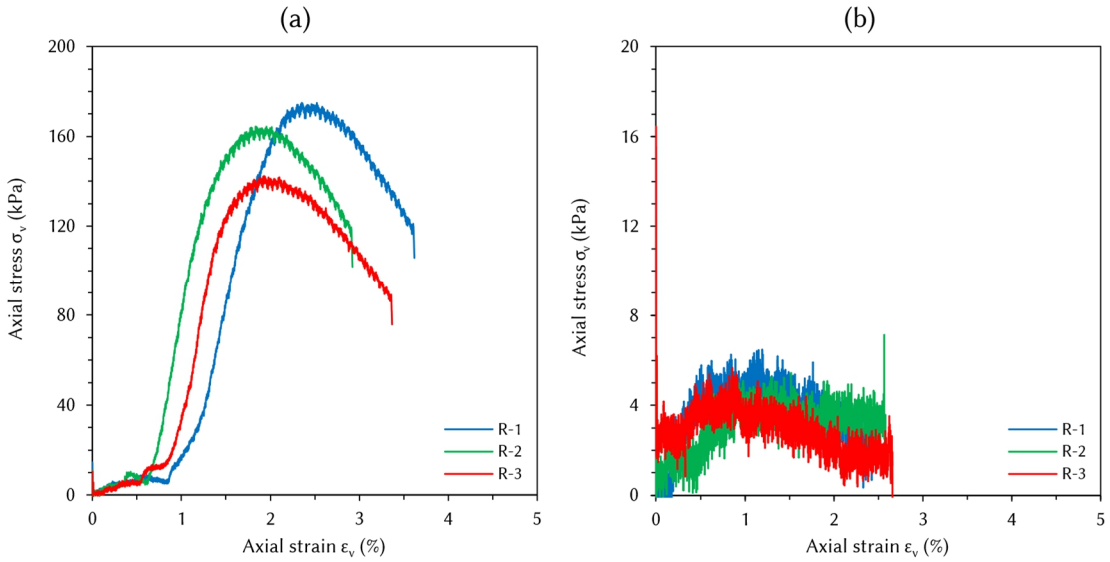


Figure A-24. Stress-strain curves of sand treated with: **(a)** 2 wt% dextrose greens, and **(b)** 4 wt% dextrose greens. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

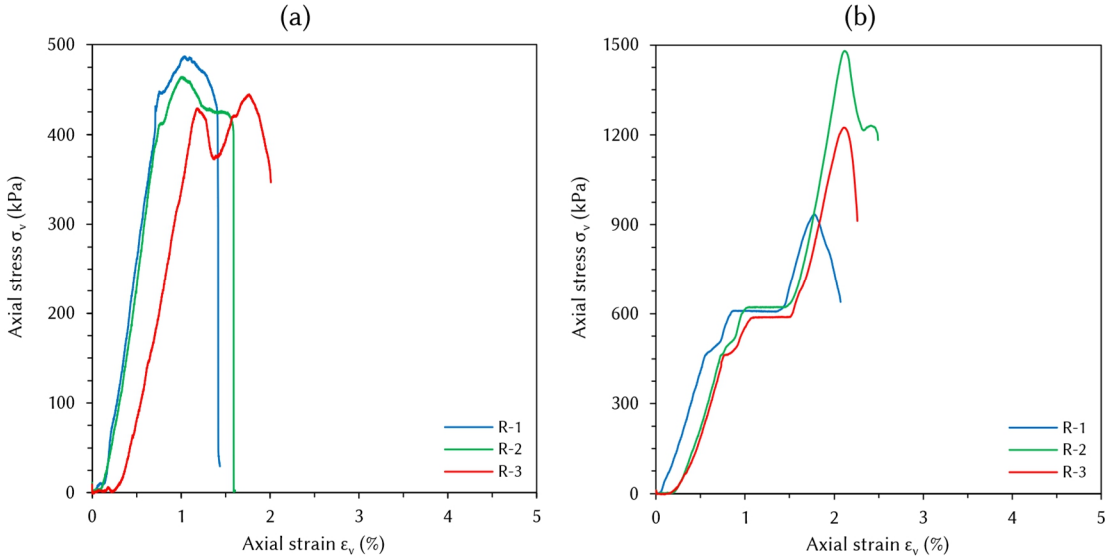


Figure A-25. Stress-strain curves of sand treated with: **(a)** 2 wt% filter concentrate, and **(b)** 4 wt% filter concentrate. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

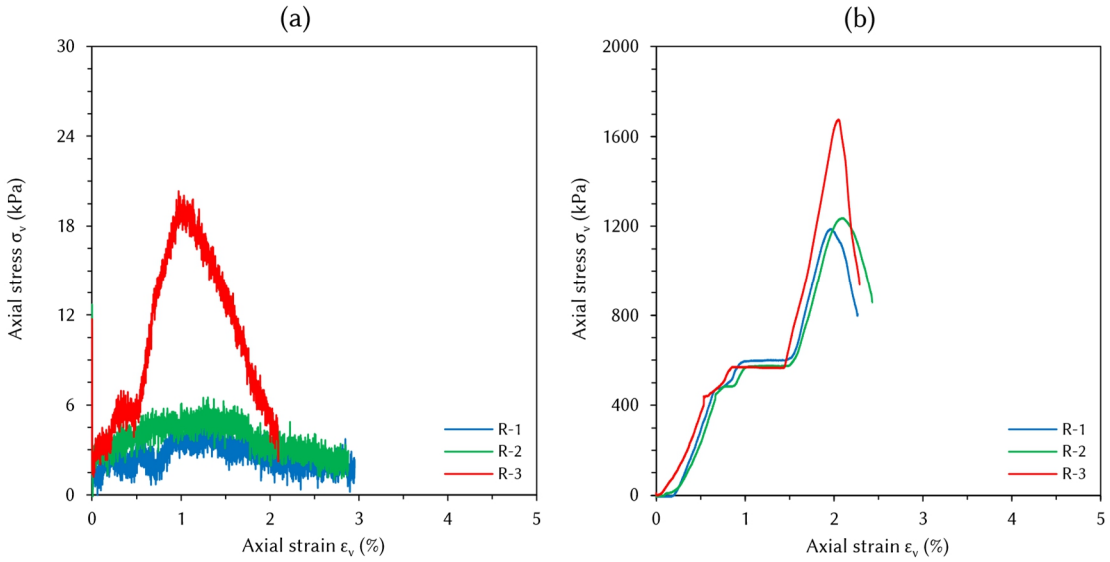


Figure A-26. Stress-strain curves of sand treated with: **(a)** 2 wt% glucose syrup retentate, and **(b)** 2 wt% rinsing water from jam production. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

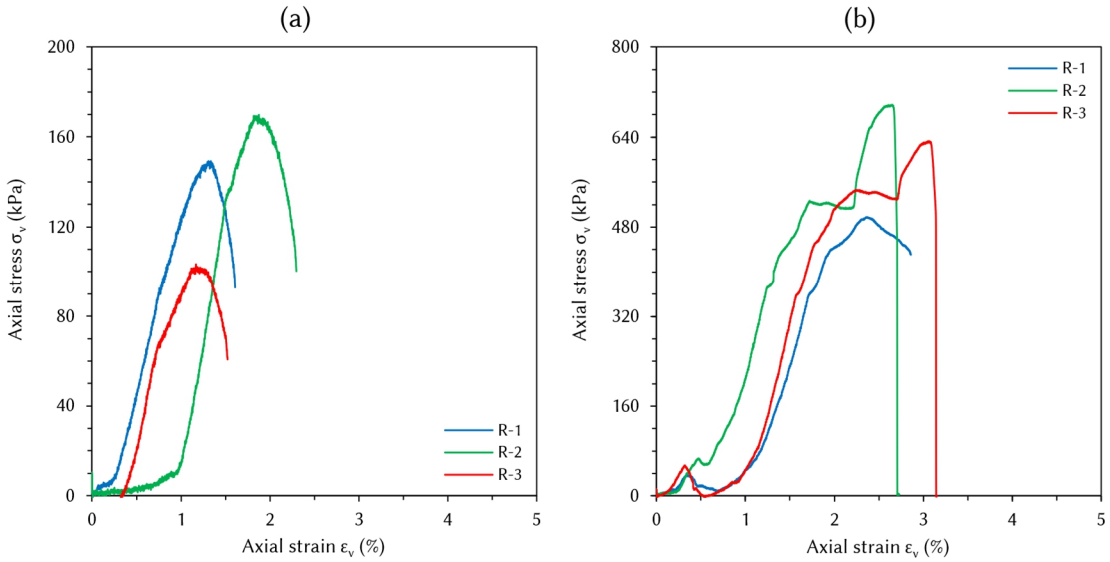


Figure A-27. Stress-strain curves of sand treated with: **(a)** 2 wt% milk permeate powder, and **(b)** 4 wt% milk permeate powder. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

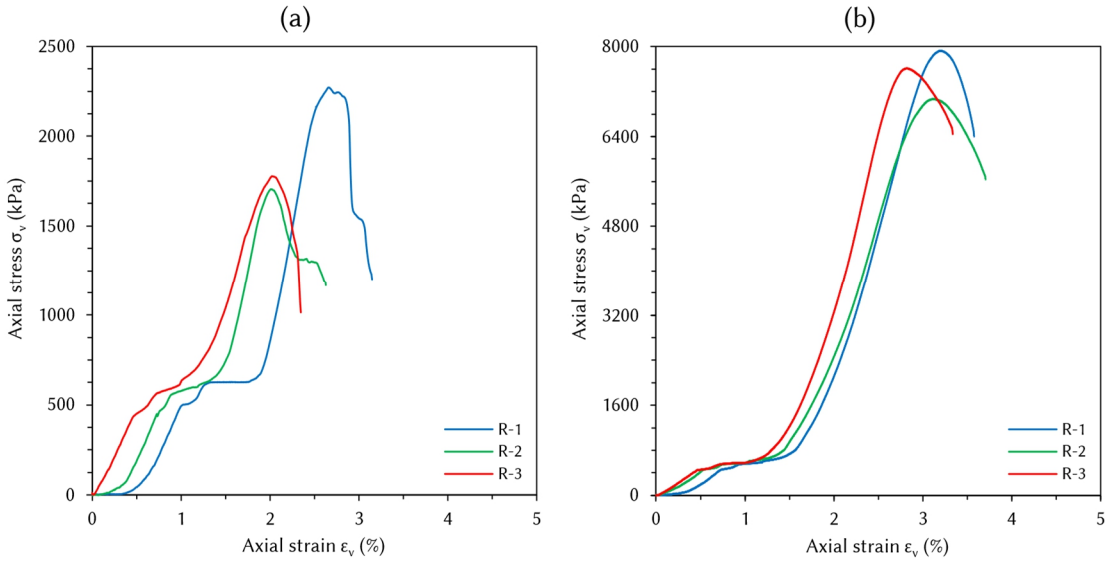


Figure A-28. Stress-strain curves of sand treated with: **(a)** 2 wt% palatinose molasses, and **(b)** 4 wt% palatinose molasses. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

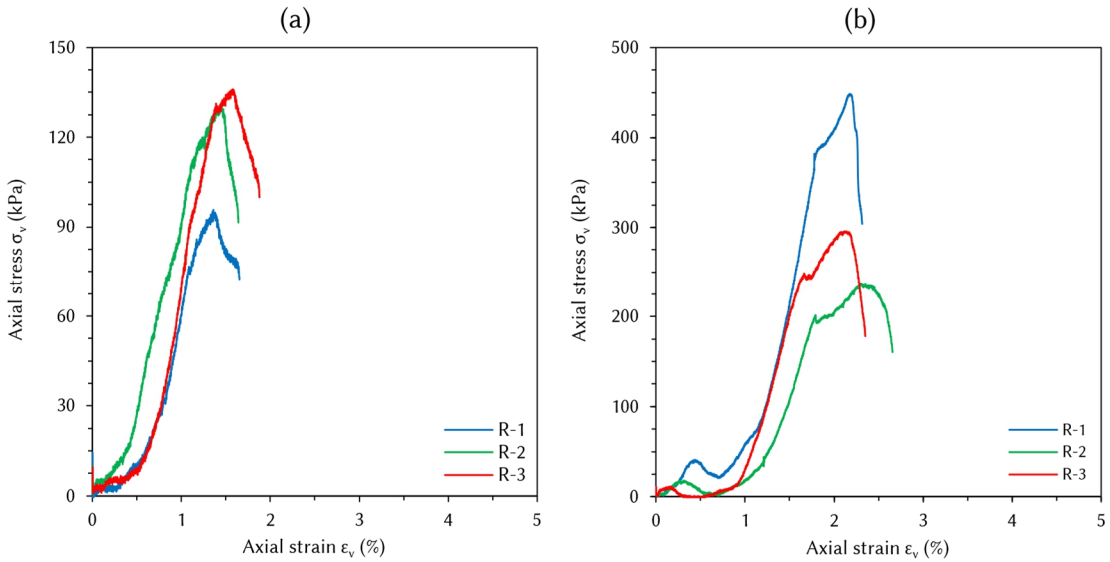


Figure A-29. Stress-strain curves of sand treated with: **(a)** 2 wt% whey permeate powder, and **(b)** 4 wt% whey permeate powder. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

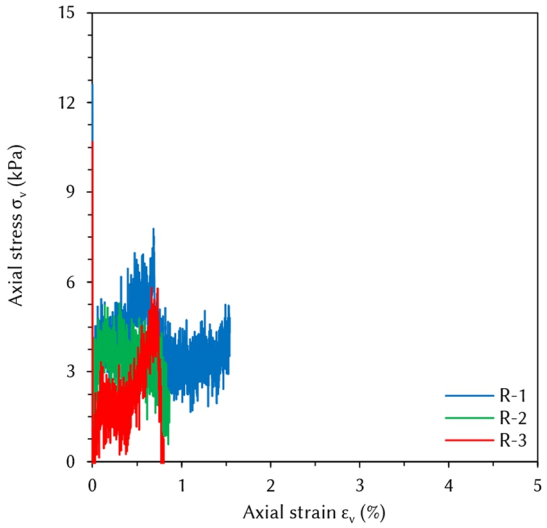


Figure A-30. Stress-strain curves of untreated sand. Abbreviations: R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3.

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Appendix B
Statistical Analysis of Laboratory Wind Erosion Test Results

Appendix B summarizes the statistical analysis of wind erosion test data detailed in Chapter 3.

Table B-1. Statistical summary of wind erosion test data – soil loss of untreated sand measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
M	64.66	13.27	5.01	3.46
SD	8.52	2.01	1.68	1.60

Note. The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-2. Statistical summary of wind erosion test data – soil loss of sand treated with water measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
M	64.66	13.27	5.01	3.46
SD	8.52	2.01	1.68	1.60

Note. Soil samples were treated with water at an application rate of 1 L/m². The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

T**able B-3.** Statistical summary of wind erosion test data – soil loss of sand treated with varying concentrations of chicory vinasses measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	1 % additive concentration			
M	5.00	23.54	18.33	23.28
SD	1.34	7.69	6.99	12.72
	2 % additive concentration			
M	1.42	13.24	9.58	17.41
SD	0.25	8.64	7.29	12.67
	3 % additive concentration			
M	1.96	5.03	3.53	11.31
SD	1.40	4.26	3.64	14.18
	4 % additive concentration			
M	0.95	3.40	4.21	16.91
SD	1.51	2.82	3.87	2.92
	5 % additive concentration			
M	0.64	2.67	1.99	14.63
SD	0.42	0.06	1.43	8.77
	6 % additive concentration			
M	0.49	1.71	1.22	11.22
SD	0.20	0.35	0.36	4.89
	7 % additive concentration			
M	0.33	1.76	1.13	7.73
SD	0.19	1.56	0.75	2.05
	8 % additive concentration			
M	0.31	1.01	0.87	6.03
SD	0.04	0.40	0.53	3.27
	9 % additive concentration			
M	0.33	1.12	0.84	6.16
SD	0.15	0.60	0.29	3.18
	10 % additive concentration			
M	0.79	0.37	0.50	1.67
SD	0.70	0.23	0.36	0.84

Note. Soil samples were treated with chicory vinasses at an application rate of 1 L/m². The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-4. Statistical summary of wind erosion test data – soil loss of sand treated with varying concentrations of corn steep liquor measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	1 % additive concentration			
M	37.52	17.89	6.63	5.39
SD	9.14	3.76	1.64	1.36
	2 % additive concentration			
M	4.05	2.96	2.63	2.34
SD	4.50	1.54	2.04	1.68
	3 % additive concentration			
M	0.51	0.48	0.24	0.37
SD	0.08	0.17	0.07	0.18
	4 % additive concentration			
M	1.91	0.32	0.14	0.18
SD	2.90	0.16	0.19	0.11
	5 % additive concentration			
M	0.21	0.24	0.04	0.12
SD	0.06	0.06	0.03	0.02
	6 % additive concentration			
M	0.14	0.21	0.04	0.08
SD	0.11	0.04	0.04	0.07
	7 % additive concentration			
M	0.13	0.11	0.04	0.04
SD	0.08	0.05	0.02	0.01
	8 % additive concentration			
M	0.10	0.14	0.01	0.03
SD	0.05	0.03	0.01	0.03
	9 % additive concentration			
M	0.11	0.11	0.02	0.02
SD	0.07	0.01	0.02	0.01
	10 % additive concentration			
M	0.17	0.18	0.01	0.03
SD	0.02	0.07	0.01	0.04

Note. Soil samples were treated with corn steep liquor at an application rate of 1 L/m². The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-5. Statistical summary of wind erosion test data – soil loss of sand treated with varying concentrations of decantation syrup measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	1 % additive concentration			
M	24.61	15.58	2.92	6.00
SD	1.85	12.61	1.07	2.72
	2 % additive concentration			
M	8.89	11.13	1.99	5.79
SD	1.13	3.10	0.26	1.99
	3 % additive concentration			
M	1.60	1.99	0.33	1.19
SD	0.45	1.47	0.26	0.65
	4 % additive concentration			
M	0.65	0.76	0.25	0.82
SD	0.31	0.53	0.09	0.33
	5 % additive concentration			
M	0.53	0.56	0.31	0.78
SD	0.09	0.21	0.12	0.42
	6 % additive concentration			
M	0.20	0.06	0.03	0.25
SD	0.04	0.03	0.02	0.12
	7 % additive concentration			
M	0.28	0.19	0.08	0.50
SD	0.02	0.12	0.03	0.25
	8 % additive concentration			
M	0.31	0.04	0.06	0.32
SD	0.04	0.03	0.01	0.37
	9 % additive concentration			
M	0.24	0.09	0.04	0.25
SD	0.04	0.05	0.02	0.03
	10 % additive concentration			
M	0.20	0.06	0.09	0.34
SD	0.03	0.04	0.03	0.06

Note. Soil samples were treated with decantation syrup at an application rate of 1 L/m². The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-6. Statistical summary of wind erosion test data – soil loss of sand treated with varying concentrations of palatinose molasses measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	1 % additive concentration			
M	23.71	8.72	2.72	3.55
SD	3.11	3.47	0.74	2.08
	2 % additive concentration			
M	4.11	3.61	0.85	1.05
SD	2.43	2.73	0.65	0.81
	3 % additive concentration			
M	1.21	0.66	0.29	0.83
SD	0.36	0.21	0.16	0.14
	4 % additive concentration			
M	0.32	0.38	0.14	0.42
SD	0.06	0.03	0.03	0.05
	5 % additive concentration			
M	0.40	0.19	0.14	0.27
SD	0.15	0.07	0.02	0.05
	6 % additive concentration			
M	0.15	0.15	0.06	0.17
SD	0.08	0.07	0.03	0.03
	7 % additive concentration			
M	0.20	0.14	0.06	0.15
SD	0.02	0.06	0.06	0.02
	8 % additive concentration			
M	0.20	0.13	0.10	0.07
SD	0.01	0.06	0.04	0.07
	9 % additive concentration			
M	0.36	0.15	0.06	0.06
SD	0.06	0.02	0.01	0.01
	10 % additive concentration			
M	0.23	0.17	0.09	0.09
SD	0.07	0.07	0.08	0.04

Note. Soil samples were treated with palatinose molasses at an application rate of 1 L/m². The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-7. Statistical summary of wind erosion test data – total weight loss of sand treated with varying concentrations of chicory vinasses, corn steep liquor, decantation syrup, and palatinose molasses after 28 days of treatment.

Parameter	Total weight loss (g)										
	Additive concentration (%)										
	0	1	2	3	4	5	6	7	8	9	10
	Chicory vinasses										
R-1	80.78	101.13	15.28	48.72	16.97	21.25	19.90	7.27	8.73	5.55	2.43
R-2	98.47	52.97	54.97	11.05	21.42	09.14	14.07	11.52	3.87	7.14	1.94
R-3	79.97	56.38	54.69	5.74	38.01	29.40	9.94	14.05	12.04	12.68	5.64
M	86.41	70.16	41.65	21.84	25.47	19.93	14.64	10.95	8.21	8.46	3.34
SD	10.46	26.87	22.83	23.43	11.09	10.19	5.00	3.43	4.11	3.74	2.01
	Corn steep liquor										
R-1	80.78	55.76	23.07	1.13	0.45	0.57	0.54	0.20	0.31	0.17	0.26
R-2	98.47	82.42	5.45	1.90	5.71	0.61	0.32	0.37	0.20	0.24	0.42
R-3	79.97	64.11	7.43	1.76	1.46	0.63	0.55	0.40	0.30	0.34	0.49
M	86.41	67.43	11.98	1.60	2.54	0.60	0.47	0.32	0.27	0.25	0.39
SD	10.46	13.64	9.65	0.41	2.79	0.03	0.13	0.11	0.06	0.09	0.12
	Decantation syrup										
R-1	80.78	37.63	21.36	6.04	3.71	2.47	0.48	0.83	0.44	0.70	0.73
R-2	98.47	44.49	32.09	2.80	1.99	1.61	0.40	1.08	1.20	0.54	0.78
R-3	79.97	65.22	29.92	6.47	1.74	2.48	0.75	1.24	0.53	0.62	0.56
M	86.41	49.11	27.79	5.10	2.48	2.19	0.54	1.05	0.72	0.62	0.69
SD	10.46	14.36	5.67	2.01	1.07	0.50	0.18	0.21	0.42	0.08	0.12
	Palatinose molasses										
R-1	80.78	39.00	6.77	2.52	1.27	0.98	0.50	0.52	0.57	0.69	0.55
R-2	98.47	34.76	17.08	3.66	1.14	0.97	0.46	0.53	0.49	0.59	0.59
R-3	79.97	42.35	4.97	2.77	1.36	1.06	0.63	0.64	0.46	0.61	0.59
M	86.41	38.70	9.61	2.98	1.26	1.00	0.53	0.56	0.51	0.63	0.58
SD	10.46	3.80	6.53	0.60	0.11	0.05	0.09	0.07	0.06	0.05	0.02

Note. The additive concentration of 0 % refers to water-treated soil. Abbreviations: M = Mean, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, SD = Standard Deviation.

Table B-8. Statistical summary of wind erosion test data – soil loss of sand treated with varying application rates of chicory vinasses measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	0.25 L/m² application rate			
M	5.83	30.14	7.86	18.90
SD	4.48	5.82	1.58	7.22

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Table B-8. *Continued from previous page.*

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	0.5 L/m² application rate			
M	3.30	25.20	8.20	6.76
SD	2.02	4.62	4.56	2.01
	0.75 L/m² application rate			
M	1.15	11.19	2.70	6.80
SD	0.99	6.65	0.84	1.82
	1 L/m² application rate			
M	0.79	0.37	0.50	1.67
SD	0.70	0.23	0.36	0.84
	1.5 L/m² application rate			
M	0.35	0.29	0.07	0.12
SD	0.06	0.19	0.06	0.09
	2 L/m² application rate			
M	0.43	0.24	0.05	0.06
SD	0.03	0.01	0.02	0.03
	2.5 L/m² application rate			
M	0.66	0.61	0.06	0.10
SD	0.07	0.04	0.01	0.03
	3 L/m² application rate			
M	0.79	0.31	0.06	0.03
SD	0.07	0.04	0.04	0.02

Note. Soil samples were treated with chicory vinasses at a concentration of 10 %. The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-9. Statistical summary of wind erosion test data – soil loss of sand treated with varying application rates of corn steep liquor measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	0.25 L/m² application rate			
M	0.17	0.26	0.57	0.85
SD	0.10	0.00	0.21	0.25
	0.5 L/m² application rate			
M	0.14	0.24	0.28	0.17
SD	0.06	0.08	0.11	0.09

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Table B-9. *Continued from previous page.*

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	0.75 L/m² application rate			
M	0.15	0.11	0.17	0.14
SD	0.04	0.09	0.08	0.04
	1 L/m² application rate			
M	0.21	0.24	0.04	0.12
SD	0.06	0.06	0.03	0.02
	1.5 L/m² application rate			
M	0.26	0.08	0.09	0.05
SD	0.06	0.03	0.03	0.05
	2 L/m² application rate			
M	0.34	0.04	0.06	0.06
SD	0.02	0.02	0.03	0.02
	2.5 L/m² application rate			
M	0.38	0.05	0.05	0.04
SD	0.03	0.02	0.03	0.03
	3 L/m² application rate			
M	0.49	0.08	0.05	0.02
SD	0.06	0.03	0.02	0.01

Note. Soil samples were treated with corn steep liquor at a concentration of 5 %. The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-10. Statistical summary of wind erosion test data – soil loss of sand treated with varying application rates of decantation syrup measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	0.25 L/m² application rate			
M	5.47	6.03	2.20	1.98
SD	4.23	3.07	0.91	0.73
	0.5 L/m² application rate			
M	1.37	3.31	3.91	1.12
SD	0.72	1.36	1.62	0.49
	0.75 L/m² application rate			
M	0.37	4.51	0.78	1.93
SD	0.23	3.54	0.24	1.49

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Table B-10. *Continued from previous page.*

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	1 L/m² application rate			
M	0.20	0.06	0.03	0.25
SD	0.04	0.03	0.02	0.12
	1.5 L/m² application rate			
M	0.42	0.06	0.19	0.22
SD	0.05	0.02	0.14	0.13
	2 L/m² application rate			
M	0.73	0.09	0.07	0.04
SD	0.11	0.02	0.02	0.04
	2.5 L/m² application rate			
M	1.14	0.09	0.03	0.05
SD	0.18	0.05	0.01	0.03
	3 L/m² application rate			
M	1.41	0.17	0.03	0.02
SD	0.12	0.04	0.02	0.01

Note. Soil samples were treated with decantation syrup at a concentration of 6 %. The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-11. Statistical summary of wind erosion test data – soil loss of sand treated with varying application rates of palatinose molasses measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	0.25 L/m² application rate			
M	2.40	2.47	4.40	2.58
SD	0.12	1.82	2.17	2.63
	0.5 L/m² application rate			
M	2.61	2.58	5.18	1.55
SD	0.49	1.43	2.23	0.37
	0.75 L/m² application rate			
M	0.57	0.12	0.52	0.18
SD	0.06	0.07	0.21	0.12
	1 L/m² application rate			
M	0.15	0.15	0.06	0.17
SD	0.08	0.07	0.03	0.03

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Table B-11. *Continued from previous page.*

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	1.5 L/m² application rate			
M	0.47	0.03	0.07	0.03
SD	0.02	0.01	0.01	0.02
	2 L/m² application rate			
M	0.26	0.06	0.03	0.02
SD	0.12	0.04	0.02	0.01
	2.5 L/m² application rate			
M	1.10	0.06	0.15	0.04
SD	0.43	0.03	0.00	0.01
	3 L/m² application rate			
M	1.85	0.14	0.03	0.05
SD	0.20	0.03	0.01	0.01

Note. Soil samples were treated with palatinose molasses at a concentration of 6 %. The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-12. Statistical summary of wind erosion test data – soil loss of sand treated with varying application rates of water measured at 2, 7, 14, and 28 days post-treatment.

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	0.25 L/m² application rate			
M	78.09	10.73	5.51	4.12
SD	8.70	2.60	1.99	1.72
	0.5 L/m² application rate			
M	72.72	9.93	6.78	5.40
SD	14.19	6.23	4.58	2.79
	0.75 L/m² application rate			
M	63.81	15.58	7.63	3.85
SD	5.58	4.29	1.99	1.07
	1 L/m² application rate			
M	64.66	13.27	5.01	3.46
SD	8.52	2.01	1.68	1.60
	1.5 L/m² application rate			
M	32.72	25.51	13.82	4.50
SD	2.24	16.39	5.29	2.17

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Table B-12. *Continued from previous page.*

Parameter	Soil loss (g)			
	Days after dust suppressant application			
	2	7	14	28
	2 L/m² application rate			
M	29.62	31.72	10.12	3.96
SD	1.19	9.56	2.50	2.33
	2.5 L/m² application rate			
M	6.57	42.13	21.09	7.54
SD	6.51	15.46	13.51	3.12
	3 L/m² application rate			
M	2.59	31.20	28.44	14.56
SD	0.21	5.81	7.31	3.24

Note. The experiments were performed with triplicate replicates (n = 3). Abbreviations: M = Mean, SD = Standard Deviation.

Table B-13. Statistical summary of wind erosion test data – total weight loss of sand treated with varying application rates of chicory vinasses, corn steep liquor, decantation syrup, and palatinose molasses after 28 days of treatment.

Parameter	Total weight loss (g)								
	Application rate (L/m²)								
	0	0.25	0.5	0.75	1	1.5	2	2.5	3
	Chicory vinasses								
R-1	120.80	54.50	38.32	25.27	2.43	1.15	0.84	1.37	1.33
R-2	120.63	70.15	50.87	26.61	1.94	0.89	0.77	1.45	1.23
R-3	127.69	63.52	41.19	13.65	5.64	0.46	0.75	1.46	1.02
M	123.04	62.72	43.46	21.84	3.34	0.83	0.79	1.43	1.19
SD	4.03	7.86	6.58	7.13	2.01	0.35	0.05	0.05	0.16
	Corn steep liquor								
R-1	120.80	1.47	1.14	0.45	0.57	0.63	0.46	0.49	0.72
R-2	120.63	1.61	0.82	0.77	0.61	0.41	0.48	0.54	0.64
R-3	127.69	2.48	0.54	0.51	0.63	0.41	0.56	0.54	0.57
M	123.04	1.85	0.83	0.58	0.47	0.48	0.50	0.52	0.64
SD	4.03	0.55	0.30	0.17	0.13	0.13	0.05	0.03	0.08
	Decantation syrup								
R-1	120.80	25.91	9.14	10.76	0.48	0.62	0.95	1.47	1.51
R-2	120.63	10.21	11.74	4.24	0.40	1.00	0.80	1.03	1.69
R-3	127.69	10.95	8.24	7.77	0.75	1.07	1.03	1.42	1.71
M	123.04	15.69	9.71	7.59	0.54	0.90	0.93	1.31	1.64
SD	4.03	8.86	1.82	3.26	0.18	0.24	0.12	0.24	0.11

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Table B-13. *Continued from previous page.*

Parameter	Total weight loss (g)								
	Application rate (L/m²)								
	0	0.25	0.5	0.75	1	1.5	2	2.5	3
	Palatinose molasses								
R-1	120.80	11.02	7.51	1.33	0.50	0.58	0.35	0.83	2.12
R-2	120.63	8.99	13.03	1.06	0.46	0.66	0.25	1.64	2.26
R-3	127.69	15.53	15.20	1.77	0.63	0.58	0.51	1.57	1.82
M	123.04	11.85	11.91	1.39	0.53	0.61	0.37	1.35	2.07
SD	4.03	3.35	3.96	0.36	0.09	0.05	0.13	0.45	0.22
	Water								
R-1	120.80	113.13	101.78	91.11	80.78	68.78	76.77	57.24	75.06
R-2	120.63	93.91	99.85	89.03	98.47	75.78	66.20	85.12	75.53
R-3	127.69	88.29	82.85	92.47	79.97	85.09	83.25	89.63	79.78
M	123.04	98.44	94.83	90.87	86.41	76.55	75.41	77.33	76.79
SD	4.03	13.03	10.42	1.73	10.46	8.18	8.61	17.54	2.60

Note. The application rate of 0 L/m² refers to untreated soil. Samples were treated with chicory vinasses, corn steep liquor, decantation syrup, and palatinose molasses at concentrations of 10, 5, 6, and 6 %, respectively. Abbreviations: M = Mean, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, SD = Standard Deviation.

Appendix C
Statistical Analysis of Laboratory Leaching Test and Field Trial Results

Appendix C summarizes the statistical analysis of leaching and field test data presented in Chapter 4.

Table C-1. Statistical summary of leaching test data – soil loss of chicory vinasses-treated sand after each wet-dry cycle.

Parameter	Soil loss (g)			
	Wet-dry cycle			
	1	2	3	4
	0.25 L/m² rainfall intensity			
M	2.68	20.37	13.03	26.97
SD	2.12	11.45	11.67	9.58
	1 L/m² rainfall intensity			
M	4.65	0.38	0.07	0.25
SD	2.45	0.06	0.03	0.24
	2 L/m² rainfall intensity			
M	0.18	0.07	0.04	0.32
SD	0.03	0.03	0.03	0.11
	4 L/m² rainfall intensity			
M	0.74	0.56	0.17	0.65
SD	0.41	0.13	0.11	0.45

Note. Abbreviations: M = Mean, SD = Standard Deviation.

Table C-2. Statistical summary of leaching test data – soil loss of corn steep liquor-treated sand after each wet-dry cycle.

Parameter	Soil loss (g)			
	Wet-dry cycle			
	1	2	3	4
	0.25 L/m² rainfall intensity			
M	0.08	0.19	1.14	2.98
SD	0.01	0.11	0.38	0.91
	1 L/m² rainfall intensity			
M	1.12	0.04	0.04	0.05
SD	0.32	0.03	0.03	0.05
	2 L/m² rainfall intensity			
M	0.31	0.05	0.05	0.29
SD	0.11	0.03	0.04	0.22
	4 L/m² rainfall intensity			
M	0.34	0.21	0.24	1.58
SD	0.20	0.04	0.06	1.18

Note. Abbreviations: M = Mean, SD = Standard Deviation.

Table C-3. Statistical summary of leaching test data – soil loss of decantation syrup-treated sand after each wet-dry cycle.

Parameter	Soil loss (g)			
	Wet-dry cycle			
	1	2	3	4
	0.25 L/m² rainfall intensity			
M	0.58	0.80	0.19	1.21
SD	0.29	0.36	0.11	0.52
	1 L/m² rainfall intensity			
M	0.11	0.01	0.07	0.02
SD	0.09	0.01	0.09	0.02
	2 L/m² rainfall intensity			
M	0.08	0.07	0.05	0.07
SD	0.02	0.02	0.02	0.03
	4 L/m² rainfall intensity			
M	0.22	0.12	0.11	0.03
SD	0.14	0.05	0.03	0.02

Note. Abbreviations: M = Mean, SD = Standard Deviation.

Table C-4. Statistical summary of leaching test data – soil loss of palatinose molasses-treated sand after each wet-dry cycle.

Parameter	Soil loss (g)			
	Wet-dry cycle			
	1	2	3	4
	0.25 L/m² rainfall intensity			
M	5.18	2.52	1.34	4.48
SD	1.27	0.33	0.86	3.40
	1 L/m² rainfall intensity			
M	0.61	0.02	0.01	0.17
SD	0.22	0.02	0.01	0.29
	2 L/m² rainfall intensity			
M	0.11	0.05	0.04	0.05
SD	0.03	0.04	0.01	0.01
	4 L/m² rainfall intensity			
M	0.27	0.11	0.07	0.06
SD	0.06	0.06	0.05	0.01

Note. Abbreviations: M = Mean, SD = Standard Deviation.

Table C-5. Statistical summary of leaching test data – soil loss of untreated sand after each wet-dry cycle.

Parameter	Soil loss (g)			
	Wet-dry cycle			
	1	2	3	4
M	108.29	10.48	4.15	2.36
SD	23.07	1.97	2.06	0.75

Note. Abbreviations: M = Mean, SD = Standard Deviation.

Table C-6 Statistical summary of leaching test data – soil loss of additive-treated sand before the first wet-dry cycle.

Parameter	Soil loss (g)			
	Substance			
	Chicory vinasses	Corn steep liquor	Decantation syrup	Palatinose molasses
M	0.09	0.12	0.04	0.03
SD	0.02	0.16	0.01	0.01

Note. Abbreviations: M = Mean, SD = Standard Deviation.

Table C-7. Statistical summary of leaching test data – total weight loss of additive-treated sand after four wet-dry cycles.

Parameter	Total weight loss (g)			
	Rainfall intensity (L/m²)			
	0.25	1	2	4
		Chicory vinasses		
R-1	80.92	8.02	0.57	1.93
R-2	26.91	2.59	0.70	1.86
R-3	81.28	5.44	0.54	2.58
M	63.04	5.35	0.60	2.12
SD	31.29	2.72	0.09	0.40
		Corn steep liquor		
R-1	5.56	1.52	0.88	3.44
R-2	3.33	0.98	0.78	2.12
R-3	4.25	1.22	0.44	1.57
M	4.38	1.24	0.70	2.38
SD	1.12	0.27	0.23	0.96
		Decantation syrup		
R-1	2.40	0.25	0.28	0.31
R-2	3.70	0.26	0.22	0.43
R-3	2.26	0.11	0.32	0.73
M	2.79	0.21	0.27	0.49
SD	0.79	0.08	0.05	0.22
		Palatinose molasses		
R-1	12.66	0.97	0.19	0.41
R-2	17.13	0.88	0.31	0.48
R-3	10.76	0.58	0.25	0.62
M	13.52	0.81	0.25	0.50
SD	3.27	0.20	0.06	0.11

Note. Abbreviations: M = Mean, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, SD = Standard Deviation.

Table C-8. Statistical summary of leaching test data – total weight loss of untreated sand after four wet-dry cycles.

Parameter	Total weight loss (g)
R-1	102.96
R-2	136.86
R-3	136.03
M	125.28
SD	19.34

Note. Abbreviations: M = Mean, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, SD = Standard Deviation.

Table C-9. Statistical summary of field trial data – mean concentrations of TSP in air sampled from chicory vinasses-, corn steep liquor-, decantation syrup-, and palatinose molasses-treated soils measured 3, 7, 14, 21, and 28 days after dust suppressant application.

Parameter	TSP (mg/m^3)				
	Days after dust suppressant application				
	3	7	14	21	28
			Chicory vinasses		
R-1	0.225	0.066	0.409	4.869	0.077
R-2	0.032	0.039	0.068	2.803	0.093
R-3	0.021	0.106	0.064	0.418	0.063
M	0.093	0.070	0.180	2.697	0.078
SD	0.171	0.068	0.725	3.933	0.194
			Corn steep liquor		
R-1	0.326	0.102	1.191	2.616	0.013
R-2	0.183	0.189	0.680	6.681	0.027 [a]
R-3	0.399	0.832	1.497	10.275	0.244
M	0.303	0.374	1.123	5.169	0.096
SD	0.697	1.586	1.522	12.140	0.232
			Decantation syrup		
R-1	0.033	0.120	0.313	7.778	0.025
R-2	0.053	0.651	0.081	0.677	0.028
R-3	0.023	0.132	0.056	0.231	0.032
M	0.036	0.301	0.150	2.896	0.028
SD	0.083	1.364	0.495	15.472	0.041
			Palatinose molasses		
R-1	0.054	0.146	0.191	9.037	0.033
R-2	0.021	0.107	0.227	7.118	0.026 [a]
R-3	0.022	0.060	0.324	9.293	0.029
M	0.032	0.104	0.247	8.483	0.030
SD	0.085	0.152	0.354	22.296	0.037
			Water		
R-1	41.863	24.631	3.554	4.899	0.084
R-2	64.807	11.430	N/A [b]	N/A [b]	N/A [b]
R-3	10.860	9.281	0.257	0.798	0.040 [a]
M	39.176	15.114	1.905	2.849	0.064
SD	32.320	13.960	3.554	4.265	0.098
			Untreated soil		
R-1	113.369	45.974	2.255	0.939	0.046
R-2	34.022	21.160	0.147	0.157	0.014 [a]
R-3	83.834	17.519	1.980	0.711	0.068

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Table C-9. *Continued from previous page.*

Parameter	TSP (mg/m³)				
	Days after dust suppressant application				
	3	7	14	21	28
M	77.075	28.218	1.461	0.603	0.043
SD	58.956	20.837	1.561	1.256	0.063
			Background load		
R-1	0.009	0.045	0.027	0.026	0.021
R-2	0.009	0.012 [a]	0.036	0.026	0.009
R-3	0.012	0.012	0.034	0.025	0.013
M	0.010	0.023	0.032	0.026	0.014
SD	0.010	0.080	0.026	0.014	0.026

Note. The background load refers to the average background particulate matter concentration logged at the test site. Abbreviations: M = Mean, N/A = Not Available, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, SD = Standard Deviation, TSP = Total Suspended Particulate.

[a] Implausible or illogical values (e.g., negative values) were removed from the data set.

[b] No data available. R-2 of the water-treated plots had to be removed from the field trial after seven days since it was extensively damaged.

Table C-10. Statistical summary of field trial data – mean concentrations of PM_{10} in air sampled from chicory vinasses-, corn steep liquor-, decantation syrup-, and palatinose molasses-treated soils measured 3, 7, 14, 21, and 28 days after dust suppressant application.

Parameter	PM_{10} (mg/m³)				
	Days after dust suppressant application				
	3	7	14	21	28
			Chicory vinasses		
R-1	0.129	0.033	0.184	4.117	0.038
R-2	0.016	0.020	0.037	2.067	0.034
R-3	0.013	0.095	0.042	0.261	0.029
M	0.053	0.049	0.088	2.148	0.034
SD	0.094	0.045	0.306	3.519	0.076
			Corn steep liquor		
R-1	0.181	0.059	0.799	1.338	0.010
R-2	0.108	0.137	0.547	4.405	0.020 [a]
R-3	0.232	0.505	1.044	6.878	0.121
M	0.174	0.234	0.796	3.184	0.051
SD	0.438	1.042	1.135	7.872	0.109
			Decantation syrup		
R-1	0.020	0.105	0.161	4.786	0.016
R-2	0.031	0.358	0.060	0.354	0.016
R-3	0.017	0.109	0.035	0.128	0.020

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Table C-10. *Continued from previous page.*

Parameter	PM_{10} (mg/m^3)				
	Days after dust suppressant application				
	3	7	14	21	28
M	0.023	0.191	0.085	1.756	0.017
SD	0.040	0.632	0.232	9.799	0.015
			Palatinose molasses		
R-1	0.036	0.114	0.112	5.247	0.017
R-2	0.018	0.053	0.130	3.976	0.022 [a]
R-3	0.015	0.035	0.192	5.786	0.015
M	0.023	0.067	0.144	5.003	0.018
SD	0.057	0.075	0.204	14.409	0.028
			Water		
R-1	32.491	18.740	3.067	3.058	0.041
R-2	42.280	9.107	N/A [b]	N/A [b]	N/A [b]
R-3	8.177	6.045	0.179	0.454	0.035 [a]
M	27.649	11.297	1.623	1.756	0.039
SD	24.394	11.206	3.170	2.747	0.054
			Untreated soil		
R-1	93.590	30.637	1.707	0.627	0.019
R-2	21.755	14.556	0.081	0.071	0.010 [a]
R-3	61.733	13.235	1.638	0.381	0.042
M	59.026	19.476	1.142	0.360	0.024
SD	52.371	14.301	1.326	0.717	0.033
			Background load		
R-1	0.008	0.035	0.023	0.023	0.013
R-2	0.008	0.010 [a]	0.026	0.021	0.007
R-3	0.011	0.011	0.024	0.019	0.008
M	0.009	0.019	0.025	0.021	0.009
SD	0.006	0.068	0.010	0.006	0.006

Note. The background load refers to the average background particulate matter concentration logged at the test site. Abbreviations: M = Mean, N/A = Not Available, PM_{10} = Particulate Matter with an aerodynamic diameter ≤ 10 μm, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, SD = Standard Deviation.

[a] Implausible or illogical values (e.g., negative values) were removed from the data set.

[b] No data available. R-2 of the water-treated plots had to be removed from the field trial after seven days since it was extensively damaged.

Table C-11. Statistical summary of field trial data – mean concentrations of $PM_{2.5}$ in air sampled from chicory vinasses-, corn steep liquor-, decantation syrup-, and palatinose molasses-treated soils measured 3, 7, 14, 21, and 28 days after dust suppressant application.

Parameter	$PM_{2.5}$ (mg/m^3)				
	Days after dust suppressant application				
	3	7	14	21	28
			Chicory vinasses		
R-1	0.071	0.017	0.093	3.677	0.026
R-2	0.012	0.013	0.024	1.720	0.023
R-3	0.010	0.088	0.027	0.191	0.016
M	0.031	0.039	0.048	1.863	0.022
SD	0.065	0.039	0.154	3.274	0.055
			Corn steep liquor		
R-1	0.117	0.037	0.577	0.841	0.008
R-2	0.078	0.099	0.481	3.352	0.014 [a]
R-3	0.160	0.327	0.793	5.372	0.054
M	0.118	0.154	0.617	2.351	0.025
SD	0.340	0.749	0.943	6.043	0.048
			Decantation syrup		
R-1	0.013	0.094	0.105	2.384	0.011
R-2	0.022	0.182	0.037	0.230	0.010
R-3	0.012	0.095	0.024	0.084	0.012
M	0.016	0.124	0.055	0.900	0.011
SD	0.024	0.223	0.152	5.047	0.008
			Palatinose molasses		
R-1	0.027	0.098	0.074	3.332	0.012
R-2	0.013	0.028	0.083	2.297	0.018 [a]
R-3	0.012	0.023	0.108	3.825	0.011
M	0.017	0.050	0.088	3.152	0.014
SD	0.043	0.050	0.138	11.445	0.026
			Water		
R-1	27.736	15.582	2.746	2.327	0.022
R-2	28.150	7.848	N/A [b]	N/A [b]	N/A [b]
R-3	7.058	4.161	0.136	0.343	0.030 [a]
M	20.981	9.197	1.441	1.335	0.027
SD	20.422	9.938	2.926	2.241	0.044
			Untreated soil		
R-1	49.834	15.948	1.440	0.490	0.011
R-2	11.658	8.152	0.053	0.041	0.006 [a]
R-3	34.743	8.677	1.447	0.194	0.021

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Table C-11. *Continued from previous page.*

Parameter	$PM_{2.5}$ (mg/m^3)				
	Days after dust suppressant application				
	3	7	14	21	28
M	32.078	10.926	0.980	0.242	0.013
SD	31.216	8.332	1.224	0.433	0.020
			Background load		
R-1	0.007	0.032	0.018	0.019	0.008
R-2	0.008	0.008 [a]	0.020	0.018	0.006
R-3	0.009	0.009	0.018	0.017	0.006
M	0.008	0.016	0.019	0.018	0.007
SD	0.003	0.067	0.005	0.003	0.002

Note. The background load refers to the average background particulate matter concentration logged at the test site. Abbreviations: M = Mean, N/A = Not Available, $PM_{2.5}$ = Particulate Matter with an aerodynamic diameter ≤ 2.5 μm, R-1 = Replicate 1, R-2 = Replicate 2, R-3 = Replicate 3, SD = Standard Deviation.

[a] Implausible or illogical values (e.g., negative values) were removed from the data set.

[b] No data available. R-2 of the water-treated plots had to be removed from the field trial after seven days since it was extensively damaged.

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Glossary

Term	Definition
Aerodynamic entrainment	Aerodynamic entrainment is one of the mechanisms by which wind-induced dust is generated. It involves the lifting of dust particles into the air by aerodynamic drag and lift forces (Shao 2008).
Agglomeration	Agglomeration is one mechanism through which dust suppressants can control wind erosion and prevent dust-sized particles from becoming airborne. Dust suppressants that act by agglomeration cause a consolidated accumulation of previously loose soil particles as they set (Parvej et al. 2021; Huertas et al. 2011).
Application method	The term "application method" refers to the technique used to apply dust suppressants. There are two fundamental methods: spray-on application and mix-in application (Piechota et al. 2004).
Application rate	The application rate refers to the volume of dust suppressant solution applied per unit surface area, typically expressed as liters per square meter (Piechota et al. 2004).
Biodegradability	Biodegradability refers to the ability of materials to decompose naturally by microorganisms into water, carbon dioxide, methane and biomass (Rudnik 2013).
Biopolymers	Biopolymers can be defined as macromolecules that are synthesized by or derived from living organisms, including plants, animals and microorganisms. They consist of monomeric units that are covalently bonded (Deb et al. 2019).
Carbohydrates	Carbohydrates are molecules composed of carbon, hydrogen and oxygen atoms and can be categorized into monosaccharides, disaccharides, oligosaccharides and polysaccharides (Wrolstad 2012).
Concentration	The concentration indicates the proportion of dust suppressant relative to the total solution, typically expressed as a percentage by weight (Piechota et al. 2004).
Disaccharides	Disaccharides, also known as double sugars, are carbohydrates composed of two monosaccharide molecules linked by glycosidic bonds. Common examples of di-

	saccharides include sucrose and lactose (Ouellette and Rawn 2015).
Disaggregation	Disaggregation is one of the mechanisms by which wind-induced dust is generated. It refers to the ejection of dust particles from soil aggregates that are undergoing saltation (Shao 2008).
Dosage rate	The dosage rate is defined as the dry weight of dust suppressant applied per unit surface area, typically expressed in grams per square meter (Xu et al. 2018)
Durability	In this thesis, the term "durability" is used to denote the extent of time a given treatment is capable of sustaining effective dust suppression without the necessity for excessive maintenance.
Dust	Dust is a generic term for solid particles that are small enough to remain suspended in the atmosphere (Cecala et al. 2012).
Dust control	Dust control, as defined in this thesis, is the practice of preventing dust-sized particles from becoming airborne, or of reducing dust particles already suspended in the air.
Dust suppressants	This thesis defines dust suppressants as materials that are applied to soil surfaces to restrict the release of dust particles into the atmosphere. In the broadest sense, the definition includes physical covers (e.g., vegetation), water and other reagents that are applied dry, in the form of emulsions, suspensions or solutions. However, the present work focuses solely on dust suppressants that are applied as liquids to mine soils. Common synonyms used for dust suppressants are dust palliatives, dust control agents, dust control products, or dust control chemicals.
Dust suppression	In this thesis, dust suppression is defined as the process of preventing dust-sized particles from becoming airborne through techniques such as applying dust suppressants.
Effectiveness	This thesis defines the term "effectiveness" as the ability of a material to achieve its intended function, quantified by the degree of improvement compared to a reference level over a specified period of time.
Emission	In environmental sciences, the term "emission" refers to the release of substances into the atmosphere from a specific source (Hajirasouliha and Zabiegaj 2021).
Environmental friendliness	Environmental friendliness, as defined in this thesis, refers to materials minimizing negative environmental impacts throughout their life cycle. In the author's

	opinion, eco-friendly dust suppressants have the following key characteristics: they are biodegradable, do not contain harmful concentrations of substances that pose a risk to ecosystems and human health, require fewer resources (i.e., water, energy, raw materials) across their value chain, and are derived from renewable sources.
Enzyme-induced calcite precipitation	Enzyme-induced calcite precipitation (EICP) is a biomineralization techniques that agglomerate soil particles through the precipitation of calcium carbonate ($CaCO_3$). EICP utilizes purified enzymes to induce the precipitation of $CaCO_3$ (Saif et al. 2022; Hamdan and Kavazanjian 2016).
Erodibility	Erodibility is the inherent resistance of rocks and soils to erosive forces (Blanco-Canqui and Lal 2008).
Field trials	In this thesis, field trials refer to experiments conducted at a mine site where treated soil plots were exposed to simulated wind forces at regular intervals using a commercial electric blower. Airborne particulate matter concentrations were measured to assess the effectiveness of the treatment under actual environmental conditions.
Food processing	Food processing is a part of the food industry and refers to the transformation of agricultural products into food, or of existing foodstuff into alternative forms (Heldman and Hartel 1997; Brennan and Grandison 2012).
Food processing by-products	Following the EU Waste Framework Directive, this thesis defines food processing by-products as biogenic materials resulting from a food processing production process where the primary objective is not the generation of that material (European Union 2008). Additionally, food processing by-products must adhere to the following criteria: (1) further use of the substance or object is certain, (2) the substance can be used directly without any further processing other than normal industrial practice, (3) the substance is produced as an integral part of a production process, (4) and further use is lawful (European Union 2008).
Food processing wastes	Following the EU Waste Framework Directive, this thesis defines food processing wastes as any biogenic material arising from a food processing production process that the holder intends or is required to dispose of (European Union 2008).

Hygroscopic salts	Hygroscopic salts are chemical compounds that can absorb moisture from the environment, thereby increasing soil moisture content and preventing dust-sized particles from becoming airborne. Common hygroscopic salts used as dust suppressants include calcium chloride and magnesium chloride (Piechota et al. 2004; Parvej et al. 2021).
Hygroscopicity	Hygroscopicity is one mechanism through which dust suppressants can control wind erosion and prevent dust-sized particles from becoming airborne. Dust suppressants that act by hygroscopicity increase the soil moisture content by absorbing water from ambient air, thereby contributing to soil cohesion (Parvej et al. 2021; Huertas et al. 2011).
Leaching test	A leaching test, as defined in this thesis, is a laboratory experiment designed to assess the effect of rainfall on the wind erosion resistance of additive-treated soil. Treated soil samples undergo varying rainfall intensities and repeated wetting-drying cycles. A laboratory wind tunnel then exposes the samples to controlled airflow conditions. Soil loss is quantified by weighing the sample tray before and after each experimental run.
Maximum dry density	The maximum dry density (MDD), is defined as the highest unit dry weight that a soil can achieve by compaction, as determined by the standard Proctor compaction test (DIN 18127:2012-09).
Microbiologically induced calcium carbonate precipitation	Microbiologically induced calcium carbonate precipitation (MICP) is a biomineralization technique that agglomerate soil particles through the precipitation of calcium carbonate ($CaCO_3$). MICP harnesses the metabolic processes of bacteria to induce the precipitation of $CaCO_3$ (Choi et al. 2020).
Mine soil	Mine soils, as defined in this thesis, are anthropogenic soils formed through mining activities and can consist of fragmented rock and native soils.
Mix-in application	Mix-in application is one of the two basic methods for applying dust suppressants. Dust suppressants are applied by incorporating them into the first substrate layer (Edvardsson 2009). This method is typical for trafficked areas, where surfaces are repeatedly graded, moistened, compacted and sprayed with the dust suppressant solution (Piechota et al. 2004).
Monosaccharides	Monosaccharides, also known as simple sugars, are carbohydrates and can exist either as polyhydroxy aldehydes or polyhydroxy ketones, with glucose and

	fructose as the most common examples (Wrolstad 2012).
Optimum moisture content	The optimum moisture content (OMC), is defined as the moisture content at which the soil attains its maximum dry density (MDD), as determined by the standard Proctor compaction test (DIN 18127:2012-09).
Particulate matter	Particulate matter (PM) is the mass fraction of total suspended particulate that is small enough to be inhaled and causes serious health problems. PM is typically subdivided into PM_{10}, and $PM_{2.5}$ (Harrison et al. 2016; Li et al. 2015).
Polysaccharides	Polysaccharides are polymeric carbohydrates composed of multiple monosaccharide units linked by glycosidic bonds. Their structure can range from 10 to 10 million monosaccharide units. As naturally occurring macromolecules, polysaccharides are classified as biopolymers. Common examples of polysaccharides include starch, glycogen and cellulose (Ouellette and Rawn 2015; Diekjürgen and Grainger 2017).
Proteins	Proteins are macromolecules consisting of amino acid residues linked by peptide bonds (Zayas 1997).
Re-application	Re-application, also known as rejuvenation, refers to the practice of applying dust suppressants after their effectiveness undercuts a specified threshold to maintain the required level of dust suppression (Thompson and Visser 2007; Edvardsson 2009).
Re-application interval	The re-application interval is the duration between the initial application of a dust suppressant and the point at which its effectiveness undercut a specified threshold, necessitating re-application to maintain the required level of dust suppression (Jones 2017; Thompson and Visser 2007)
Saltation bombardment	Saltation bombardment is one of the mechanisms by which wind-induced dust is generated. It entails the dislodgement of dust particles from soil aggregates due to the impact of saltating sand grains (Shao 2008).
Soil loss	In this thesis, soil loss is a metric to quantify wind erosion resistance. Soil samples are placed in a wind tunnel and subjected to controlled airflow conditions. The sample tray is weighed both before and after each experimental run (Lemboye et al. 2021).
Soil stabilization	Soil stabilization refers to practices used to enhance the engineering properties of soil, including its mechanical strength, permeability and compressibility (Hataf et al. 2018; Karol 2003).

Soil stabilizer	Soil stabilizers are materials used to improve the engineering properties of soil, including its mechanical strength, permeability and compressibility. Examples of common soil stabilizers are lime fly ash, tree resin and synthetic polymers (Karol 2003).
Spray-on application	Spray-on application is one of the two basic methods for applying dust suppressants. Dust suppressants are applied by spraying them directly onto the surface, which can be done either in one heavy application or in several light applications (Edvardsson 2009; Jones 2017).
Standard Proctor compaction test	According to DIN 18127:2012-09, the standard Proctor compaction test is a laboratory test to determine the optimal moisture content (OMC) at which a given soil achieve its maximum dry density (MDD).
Synthetic polymers	Synthetic polymers, typically derived from petrochemicals, are macromolecules composed of repeating monomer units connected by covalent bonds. They are often used as dust suppressants, with common examples including polyvinyl acetate and vinyl acrylic (Bolander and Yamada 1999; Campbell 2000).
Total suspended particulate	Total suspended particulate (TSP) are all particles of solid and liquid droplets suspended in the air, with no specified size limit. However, they are typically less than 100 micrometer in diameter (Larssen and Hagen 1996).
UCS test	According to DIN EN ISO 17892-7:2018-05, the UCS test is a laboratory test used to determine the unconfined compressive strength of a cylindrical sample of material.
Unconfined compressive strength	The unconfined compressive strength (UCS) is defined as the maximum axial compressive stress that a cylindrical sample of material can withstand under unconfined conditions (DIN EN ISO 17892-7:2018-05).
Watering	Watering refers to the application of water to exposed soil surfaces such as haul roads, stockpiles and benches to suppress dust emissions. It is one of the most common and traditional dust suppressants used at mine sites (Cecala et al. 2012).
Wind erosion	Wind erosion is the physical process in which sediment is moved by the action of wind (Shao 2008).
Wind erosion control	This thesis defines wind erosion control as the practice of preventing the movement of soil particles by the forces of wind.

Wind erosion test	The wind erosion test, as defined in this thesis, is a laboratory experiment designed to determine the resistance of a given soil to wind erosion. Soil samples are placed in a wind tunnel and exposed to controlled airflow conditions. Soil loss is quantified by weighing the sample tray before and after each experimental run.
Wind-blown dust	In this thesis, wind-blown dust is defined as dust-sized soil particles which are suspended into the air as a result of wind erosion.

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Supplementary Data

Supplementary data are provided on the accompanying SD card, granting interested parties with the opportunity to rigorously review the findings presented in this thesis. The SD card includes but are not limited to the following data:

- Primary soil characterization data, including pH, color, particle size distribution, specific gravity, mineralogy, and geochemistry.
- Primary data on dry matter and moisture content of tested food processing wastes and by-products.
- Material data sheets related to tested food processing wastes and by-products.
- Personal communications.
- Primary standard Proctor compaction test data.
- Primary UCS test data, including high-resolution images of UCS samples after failure.
- Primary wind erosion test data.
- Primary leaching test data.
- Primary field test data, including high-resolution images of each soil surface before and after each measurement.
- Meteorological data from the field experiments.

A digital copy can also be provided upon request. Please contact the author at ds.research@posteo.de.