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Integrating Multi-Tier Tree Walls for Sustainable Dust Control in Mining Operations

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Abstract: This study evaluates multi-tier vegetative barriers as a sustainable approach to dust control in mining operations. Through a synthesis of peer-reviewed literature and field studies, we analyse dust suppression mechanisms, species-specific performance, and optimal design parameters, including canopy density and barrier alignment with prevailing winds. Findings show that well-designed vegetative barriers can reduce airborne particulate matter, including hazardous PM2.5 and PM10, by up to 84% compared to unmanaged sites, effectively mitigating dust dispersion at mine boundaries. The study highlights the role of species with high leaf surface roughness and trichome density in enhancing dust capture and provides guidelines for barrier layout. Beyond air quality improvement, these barriers support environmental restoration, carbon sequestration, and ecosystem health. Practical recommendations are offered for implementing vegetative barriers in mining environments, alongside directions for future research

Keywords: dust suppression, vegetative barrier, mining operations, air quality, multi-tier vegetation, canopy density, species selection, dust mitigation, PM2.5, PM10, environmental restoration, carbon sequestration

I. INTRODUCTION

Mining operations, while essential for economic development, are a significant source of atmospheric pollution. Activities such as excavation, transportation, and processing of minerals release vast quantities of dust into the atmosphere, posing a considerable threat to environmental quality and human health. This dust, composed of particulate matter (PM), includes coarse particles as well as finer, more hazardous fractions like PM10 and PM2.5, which can penetrate deep into the respiratory system. The concentration of these pollutants in mining zones often exceeds national air quality standards, impacting local communities and ecosystems.

Traditionally, dust control in mines has relied on mechanical or chemical methods, such as water sprinkling and the use of chemical suppressants. While effective to an extent, these methods can be resource-intensive, requiring large amounts of water and continuous operational oversight. In the search for more sustainable and ecologically integrated solutions, the use of vegetative barriers, or "tree walls," has emerged as a promising approach. These barriers, consisting of strategically planted trees and shrubs, function as natural filters, mitigating dust dispersion while offering numerous co-benefits.

While many studies have examined individual aspects of vegetative barriers, a comprehensive synthesis that integrates species selection, structural design, and ecological co-benefits specifically for the mining context is lacking. This review aims to fill that gap by synthesizing existing research to evaluate the efficacy of multi-tier vegetative barriers as a sustainable dust control strategy in mining operations. We explore the fundamental mechanisms of dust capture by vegetation, the critical factors influencing barrier performance, such as species selection and structural design, and the broader ecological advantages of this approach. By integrating findings from field studies, laboratory experiments, and wind tunnel simulations, this paper provides a comprehensive overview of how living walls can be effectively integrated into mining landscapes to improve air quality and promote environmental restoration.

II. METHODOLOGY AND REVIEW PROCESS

This literature review was conducted to systematically synthesize and evaluate the existing knowledge on the use of vegetative barriers for dust control in mining operations. The review process was structured following the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to enhance methodological rigor and transparency.

Search Strategy: A comprehensive search of scientific literature was performed using multiple academic databases, including Scopus, Web of Science, and Google Scholar. The search was conducted using a combination of keywords and their variants: ("dust suppression" OR "dust control" OR "particulate matter mitigation") AND ("vegetative barrier" OR

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"green wall" OR "shelterbelt" OR "tree wall") AND ("mining operations" OR "mine site" OR "quarry"). The search was limited to publications from January 2011 to June 2025 to ensure the inclusion of recent advancements in the field.
Study Selection and Quality Assessment: The inclusion criteria for literature were: (1) peer-reviewed journal articles, conference proceedings, or book chapters; (2) studies focusing on the use of vegetation to mitigate airborne particulate matter (PM2.5, PM10, or total suspended particulates); (3) studies conducted in mining, industrial, or analogous high-dust environments (e.g., roadsides); and (4) articles published in English. Exclusion criteria included news articles, non-peer-reviewed reports, and studies where dust control was not a primary outcome. The quality of the selected sources was assessed based on the clarity of their methodology, the robustness of their data, and their publication in reputable, peer-reviewed venues.

III. Dust Suppression Mechanisms of Vegetative Barriers

Vegetative barriers reduce airborne dust concentrations through a combination of physical and biological processes that alter airflow and capture particulate matter. The effectiveness of these natural filters is not based on a single mechanism but on the interplay of several factors related to the barrier's structure and the characteristics of the dust particles. The primary mechanisms include filtration, sedimentation, and impaction, which collectively reduce the amount of dust that escapes the mine boundary.

The fundamental principle behind a vegetative barrier is its ability to modify wind patterns. A dense, multi-tiered wall of trees and shrubs acts as a porous obstacle, forcing air to slow down and move around or through it. This reduction in wind velocity is critical; as the air slows, its capacity to carry suspended particles decreases, causing heavier particles to fall out of suspension due to gravity—a process known as sedimentation. This mechanism is most effective for larger particles. Studies conducted in wind tunnels have demonstrated that vegetation can significantly reduce downwind air speeds, creating a calmer zone where dust can settle.

As the dust-laden air passes through the canopy, particles collide with and adhere to the surfaces of leaves, twigs, and branches. This process, called impaction or interception, is a primary mechanism for capturing finer particles that are less affected by gravity. The complex and extensive surface area provided by a multi-layered canopy creates an efficient filter. The effectiveness of impaction depends on particle size, wind speed, and the physical characteristics of the plant surfaces. Research has shown that even fine particles like PM2.5 can be effectively captured through this mechanism, particularly by plants with specific leaf traits.

Beyond passive capture, the cumulative effect of these mechanisms can lead to a significant reduction in ambient dust levels. It is important to distinguish the performance of vegetative barriers from engineered solutions. For instance, advanced ventilation and dust removal systems in mining can achieve dust concentration reductions of up to 84.12% in targeted environments. While vegetative barriers may not reach such high efficiencies, they offer a substantial and sustainable alternative. Well-designed green hedges have been shown to reduce PM concentrations by up to 39% in controlled settings. While valuable, it is critical to acknowledge that findings from controlled wind tunnel studies may not fully replicate the complex atmospheric dynamics of an open-pit mine, a limitation in the current literature. Nonetheless, the evidence strongly suggests that integrating vegetative barriers can complement and enhance existing dust control measures, leading to a substantial improvement in air quality around mining operations.

IV. Key Factors in Designing Effective Vegetative Barriers

The success of a vegetative barrier for dust control depends heavily on thoughtful design and planning. Simply planting trees is not enough; the selection of appropriate species, the structural arrangement of the planting, and its orientation relative to the dust source and prevailing winds are all critical factors that determine its effectiveness.

A. Species Selection for Optimal Dust Capture

The choice of plant species is arguably the most important factor in designing a vegetative barrier. Different species possess unique morphological and physiological traits that influence their ability to tolerate pollutants and capture dust. The ideal species are those that are resilient to the harsh conditions of a mining environment and have physical characteristics that maximize particle interception.

Leaf surface characteristics are paramount for dust capture. Research consistently shows that species with rough, hairy, or waxy leaves are more effective at trapping and retaining dust than those with smooth surfaces. Microscopic features such as trichomes (leaf hairs) and epicuticular waxes increase the leaf's surface area and create a complex texture that

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particles readily adhere to. For instance, studies on various evergreen species revealed that the roughness of the leaf surface, the waxy layer, and the structure of stomata all influence the retention of particulate matter. Species like Shorea robusta, Mangifera indica, and Ficus religiosa have demonstrated high dust-capturing capacities and are considered excellent choices for plantation in polluted zones.

Canopy structure and density also play a vital role. Trees with dense, compact canopies provide a more formidable barrier to airflow and offer a greater surface area for impaction. Evergreen species are often preferred over deciduous ones because they provide year-round dust suppression, which is crucial for continuous mining operations. Another key consideration is the Air Pollution Tolerance Index (APTI), a composite metric calculated from four key physiological and biochemical parameters of a plant's leaves: ascorbic acid content, total chlorophyll, relative water content, and leaf extract pH. The APTI provides a quantitative measure of a plant's ability to withstand air pollution stress, making it a valuable tool for selecting resilient species for long-term barrier sustainability.

B. Structural Design of Multi-Tier Barriers

The spatial arrangement of the vegetation, or the barrier's architecture, is crucial for optimizing its aerodynamic performance. A multi-tier design, which combines taller trees with shorter trees and shrubs, is considered the most effective configuration. This layered structure creates a dense barrier from the ground up to the tree canopy, minimizing gaps through which dust-laden wind can pass.

The key design parameters include the barrier's height, width, and porosity (or density). Height is important for intercepting dust plumes that may rise above the ground. Width, or the number of rows of trees, contributes to the overall density and filtering capacity of the barrier. Porosity determines how much air can pass through the barrier versus how much is deflected over and around it. The literature presents a nuanced view on barrier density. While a dense barrier seems intuitive for better filtration, some studies caution that overly dense structures can increase turbulence on the leeward side, potentially re-suspending settled dust. This suggests an optimal, rather than maximal, density is required, a finding that warrants further site-specific investigation.

Wind tunnel experiments have shown that the interception efficiency for PM varies with wind speed, with efficiency generally decreasing as wind speed increases. Therefore, the barrier should be designed to significantly reduce wind velocity. The orientation of the barrier is also critical. To be most effective, the vegetative wall should be planted perpendicular to the direction of the prevailing winds blowing from the dust source. This alignment ensures that the maximum amount of dust-laden air interacts with the vegetative filter before it can disperse into the surrounding environment.

V. CO-BENEFITS AND ENVIRONMENTAL RESTORATION

While the primary goal of integrating multi-tier tree walls in mining operations is dust control, their benefits extend far beyond air quality improvement. These vegetative barriers are a cornerstone of ecological restoration, helping to heal landscapes degraded by mining and fostering the return of biodiversity. They represent a sustainable, multi-functional solution that aligns with broader environmental goals, including carbon sequestration and soil health improvement.

A. Ecological Restoration of Mine-Degraded Lands

Mining activities often leave behind barren landscapes with compacted, nutrient-poor soil. Establishing vegetation is a crucial first step in reclaiming these lands. The plants selected for dust barriers, particularly hardy, native species, can initiate the process of ecological succession. Their root systems help to break up compacted soil, improving its structure, aeration, and water infiltration capacity. As leaves and other organic matter decompose, they enrich the soil with essential nutrients, gradually rebuilding the topsoil layer that was lost during mining.
This process of soil development is fundamental to restoring a functioning ecosystem. Studies on the revegetation of coal mine-degraded lands show that plant growth significantly improves soil properties, including increasing organic carbon, nitrogen, and phosphorus levels while lowering pH and bulk density. Over time, the improved soil conditions can support a wider variety of plant life, creating a more diverse and resilient ecosystem. This transformation turns a source of pollution into a habitat for local wildlife, supporting insects, birds, and other animals.

B. Carbon Sequestration and Climate Change Mitigation

In addition to restoring local ecosystems, vegetative barriers contribute to global climate change mitigation through

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carbon sequestration. As trees and shrubs grow, they absorb atmospheric carbon dioxide (CO2) through photosynthesis, storing carbon in their biomass (trunks, branches, leaves, and roots) and in the surrounding soil. A mature, multi-tiered forest can act as a significant carbon sink, helping to offset the greenhouse gas emissions associated with mining operations and machinery.

The integration of these green infrastructures into mining landscapes thus serves a dual purpose: addressing a local pollution problem while contributing to a global environmental solution. This synergy underscores the sustainability of using vegetative barriers. They not only provide an immediate and effective method for dust suppression but also offer a long-term investment in environmental health, transforming mining liabilities into ecological assets. Furthermore, these green belts improve the aesthetic quality of the landscape, creating a visual buffer between the industrial site and surrounding communities, which can improve public perception and social license to operate.

VI. Conclusion and Future Directions

The integration of multi-tier vegetative barriers presents a scientifically sound, sustainable, and multi-functional strategy for dust control in mining operations. This review of existing literature confirms that strategically designed tree walls can significantly mitigate the dispersion of harmful particulate matter. The effectiveness of these barriers hinges on a holistic approach that considers species-specific traits, such as high leaf surface roughness and trichome density, alongside optimal structural design, including canopy density and alignment with prevailing winds.

Beyond their primary function of improving air quality, these green infrastructures are powerful tools for environmental restoration. They initiate the process of soil regeneration on degraded mine lands, enhance biodiversity, and act as valuable carbon sinks, contributing to both local ecological health and global climate change mitigation. This dual benefit positions vegetative barriers as a superior alternative to purely mechanical or chemical dust suppression methods, offering a long-term, self-sustaining solution that adds ecological and aesthetic value to the landscape.

However, a critical evaluation of the existing literature reveals several gaps and limitations. Many studies are geographically concentrated, particularly in regions like India, and their findings may not be directly transferable to different climatic or geological contexts. Furthermore, the heterogeneity of study designs and reported metrics makes direct statistical synthesis or meta-analysis challenging. To address these gaps and refine the application of vegetative barriers, future research should be prioritized in the following areas:

1. Standardized Long-Term Monitoring: What are the most effective, standardized metrics for reporting barrier performance, and how does dust capture efficiency evolve over a 5–10 year period to enable robust cross-study comparisons and potential meta-analysis?

2. Industry-Specific Species Trials: How does the dust capture effectiveness of selected plant species vary based on the specific type of mining (e.g., coal, iron, copper), considering the unique chemical and physical properties of the dust generated?

3. Development of Integrated Systems: What are the synergistic effects of combining vegetative barriers with other dust control technologies, such as automated water sprinkling systems or engineered ventilation, to create optimized hybrid systems?

4. Socio-Economic and Comprehensive Cost-Benefit Analysis: What is the full economic and social return on investment for vegetative barriers when co-benefits such as carbon sequestration, improved public health, and enhanced ecosystem services are included in the valuation?

In conclusion, multi-tier tree walls are not merely a passive barrier but a dynamic, living system that offers a robust and sustainable solution to one of the mining industry's most persistent environmental challenges. Their implementation represents a critical step towards a greener, more responsible mining sector.

REFERENCES

[1]. M. Yadav, N. K. Singh, S. P. Sahu, D. Garnayak, and S. K. Sahu, “Impact of mining and allied activities on air quality of a mega coal mining zone in India,” Environ. Qual. Manage., vol. 34, no. 4, June 2025, doi: 10.1002/tqem.70089.

DOI: 10.17148/IARJSET.2025.12725

[2]. Kamesh, B. P. Singh, S. Misra, and . R., "Evaluating the tolerance and dust capturing capacity of tree species affected by coal dust polluted area," Nat. Environ. Pollut. Technol., vol. 24, no. S1, pp. 223–233, Jan. 2025, doi: 10.46488/nept.2024.v24is1.016.
[3]. X. Wang, J. Zhao, Y. Li, and Z. Li, "Optimized design and performance evaluation of long-pressure-short-extraction ventilation and dust removal system based on the Coanda effect," Front. Artif. Intell., vol. 8, Apr. 2025, doi: 10.3389/frai.2025.1565889.
[4]. M. Biocca, D. Pochi, G. Imperi, and P. Gallo, "Reduction in atmospheric particulate matter by green hedges in a wind tunnel," Agriengineering, vol. 6, no. 1, pp. 228–239, Jan. 2024, doi: 10.3390/agriengineering6010014.
[5]. S. Panicker et al., "Online coal dust suppression system for opencast coal mines," Int. J. Coal Sci. Technol., vol. 10, no. 1, Dec. 2023, doi: 10.1007/s40789-023-00624-2.
[6]. J. Chen, I. M. Jiskani, and G. Li, "Ecological restoration of coalmine-degraded lands: influence of plant species and revegetation on soil development," Sustainability, vol. 15, no. 18, p. 13772, Sept. 2023, doi: 10.3390/su151813772.
[7]. L. Q. R. Ossanna, K. Serrano, L. L. Jennings, J. Dillon, R. M. Maier, and J. W. Neilson, "Progressive belowground soil development associated with sustainable plant establishment during copper mine waste revegetation," Appl. Soil Ecol., vol. 186, p. 104813, June 2023, doi: 10.1016/j.apsoil.2023.104813.
[8]. M. J. Kwak et al., "Understanding particulate matter retention and wash-off during rainfall in relation to leaf traits of urban forest tree species," Horticulturae, vol. 9, no. 2, p. 165, Jan. 2023, doi: 10.3390/horticulturae9020165.
[9]. Y.-T. Pu, Y.-Y. Jia, M.-X. He, W.-S. Yao, X.-Q. Mo, and J.-J. Tao, "Surface microcosmic structure and dust retention amounts of five evergreen species," E3S Web Conf., vol. 393, p. 2034, 2023, doi: 10.1051/e3sconf/202339302034.
[10]. M. P. Srivastava and K. Awasthi, "Assessment of Roadside Plants as Barriers for Control Pollution of Some Districts of Uttar Pradesh:Green National Corridor," IJPE, vol. 7, no. 04, pp. 280–286, Dec. 2021, doi: 10.18811/ijpen.v7i04.7.
[11]. L. Guo et al., "Evaluation of conifer and broad-leaved barriers in intercepting particulate matters in a wind tunnel," J. Air Waste Manage. Assoc., vol. 70, no. 12, pp. 1314–1323, Dec. 2020, doi: 10.1080/10962247.2020.1799883.
[12]. M. J. Kwak et al., "Surface-based analysis of leaf microstructures for adsorbing and retaining capability of airborne particulate matter in ten woody species," Forests, vol. 11, no. 9, p. 946, Aug. 2020, doi: 10.3390/f11090946.
[13]. D. Chakraborty, S. Singh, and P. Kumar, "Evaluation of atmospheric dust deposition rates and their mineral characterization in copper and iron mining areas, singhbhum, india," J. Air Waste Manage. Assoc., vol. 70, no. 9, pp. 964–976, 2020, doi: 10.1080/10962247.2020.1818647.
[14]. J. Pandit, A. Sood, S. Bhardwaj, and A. Sharma, "Seasonal variation of leaf dust accumulation and biochemical parameters of selected plant species alongside the national highway-7 in sirmaur, H.P, india," Curr. World Environ., vol. 12, no. 2, pp. 421–428, Aug. 2017, doi: 10.12944/cwe.12.2.26.
[15]. N. Singh, S. K. Bhardwaj, K. S. Pant, and T. S. Rai, "Determination of leaf dust accumulation on certain plant species grown alongside national highway- 22, india," Curr. World Environ., vol. 11, no. 1, pp. 77–82, Apr. 2016, doi: 10.12944/cwe.11.1.10.
[16]. John Tatarko, David G Walker, and Simon J Van Donk, "Applications of WEPS and SWEEP to non-agricultural lands," in International Symposium on Erosion and Landscape Evolution (ISELE), 18-21 September 2011, Anchorage, Alaska, St. Joseph, MI: American Society of Agricultural and Biological Engineers, 2011, doi: 10.13031/2013.39234.