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Assessing the growth response and behavioral adaptations of *Eucalyptus camaldulensis* to dust pollution

Aneeqa Sarfraz[1], Muhammad Azeem Sabir[1], Tanveer Hussain Turabi [1], Fahad Rasheed[2], Hafiz Muhammad Furqan Shaheen[2], and Muhammad Talha Bin Yousaf[3*], Shahid Ali Khan[4*]
[1]Institute of Forest Sciences, The Islamia University of Bahawalpur, Bahawalpur, 63100, Punjab, Pakistan
[2]Department of Forestry and Range Management, University of Agriculture Faisalabad, Faisalabad, 38040, Punjab, Pakistan
[3]Department of Forestry, College of Agriculture, University of Sargodha, Sargodha, 40100, Punjab, Pakistan
[4]Office of Research, Innovation and Commercialization, PMAS-Arid Agriculture University, Rawalpindi, 46300, Punjab, Pakistan

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Abstract

Dust pollution poses significant environmental challenges, affecting plant growth and ecosystem stability in both natural and managed environments. Eucalyptus camaldulensis, commonly known as the River Red Gum, is an important tree species due to its rapid growth, adaptability, and widespread use in reforestation and land reclamation programs. This study was designed to evaluate the growth potential and physiological responses of Eucalyptus camaldulensis under different levels and sources of dust pollution. A pot experiment was conducted in the experimental area of the Institute of Forest Sciences, The Islamia University of Bahawalpur, Pakistan. Five treatments were applied, including T_1 (Control), T_2 (Charcoal dust), T_3 (Wood dust), T_4 (Soil dust), and T_5 (Cement dust), each with three replicates to ensure statistical reliability. The results showed that dust pollution significantly affected plant physiological performance, while Eucalyptus camaldulensis exhibited moderate tolerance under stress conditions. The maximum chlorophyll a and chlorophyll b contents (0.94 mg g^{-1} FW and 0.67 mg g^{-1} FW, respectively) were recorded in the control treatment (T_1), whereas the minimum values (0.52 mg g^{-1} FW and 0.41 mg g^{-1} FW, respectively) were observed under charcoal dust (T_2). Overall, charcoal dust was the most harmful treatment, followed by cement, soil, and wood dust in terms of negative effects on physiological attributes. This study highlights the potential role of Eucalyptus camaldulensis in mitigating dust pollution impacts. The findings provide useful insights into plant stress physiology and support its application in environmental management, urban plantations, and ecological restoration programs.

1. Introduction

Dust pollution, resulting from natural processes and anthropogenic activities, is a major environmental concern (Adewumi et al., 2022). It can degrade air quality, affect human health, and disrupt plant growth (Ahmad et al., 2022; Mama et al., 2020). The annual dust emissions total 30 million tons. Agricultural, energy, cement, and other Indus-tries, as well as road dust and the movement of large vehicles on unpaved roads, contribute to dust pollution (Wu et al., 2016). Office and construction workers are also at risk of serious health problems due to construction dust, which can be produced by a variety of activities, including excavations, drilling, transportation of bulk materials, loading and unloading, outdoor storage of materials, mixing of concrete and mortar, cut-and-fill operations, and machine movement.

Corresponding Author: *Muhammad Talha Bin Yousaf Email: talha.yousaf@uos.edu.pk
**Shahid Ali Khan ddp@uaar.edu.pk

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Demolition activities generate the most dust, with concrete and masonry demolition exposing workers to respirable crystalline silica (Halvorsen et al., 2025). Silt, wind, dry weather, and mechanical disturbances can also increase dust pollution (Katra, 2020). Industrial air pollution is often caused by dust, which poses a threat to all forms of life. In India, air quality is negatively affected by dust, accounting for 35% of pollution (Roy et al., 2024). Finely divided solid particles can be carried by the wind, contributing to atmospheric pollution. Dust from human activities, such as road transport, stone crushers, and coal-based thermal and cement industries, also contributes to this problem. Dust accumulation on leaves can increase road salt penetration and water stress and can affect the visible and shortwave infrared reflectance of leaves (Chaudhary and Rathore, 2019). Cement dust, with a pH greater than 9, can damage leaf tissues and alter soil pH. The presence of Ni, Co, Pb, and Cr in cement dust poses microbiological hazards. Cement dust is detrimental to ecosystems, humans, animals, and plants (Adewumi et al., 2022). Trees must adapt their ecophysiology to survive adverse environments, as environmental stress disrupts the balance of plant systems. Physiological mechanisms that accumulate airborne pollutants may help plants survive in hostile conditions (Molina & Segura, 2021). However, increasing levels of dust deposition are detrimental. Airborne particulate pollution harms the delicate leaves of trees (Mandal et al., 2023). Some tree species are better equipped to remove dust, thereby improving urban air quality. Dust has a significant influence on ecosystems, human health, plant physiology, and ecological interactions (Singh et al., 2020). Leaf dust reduces photosynthesis by obstructing gas exchange and water absorption. Dusty leaves can absorb 2–3 °C more heat than dust-free leaves, hindering tree growth (Farooq et al., 2020). The following factors are important for plants: leaf area, epidermal thickness, height, and crown structure (Singh et al., 2021). The presence of airborne dust can reduce chlorophyll production and ultimately deplete leaf tissue iron, which may harm plants (Nawaz et al., 2021). Although the effects of small dust particles on plants are not fully understood, they may cause stress and result in loss of biomass. Moreover, dust deposition on epiphytic lichen or sphagnum communities may alter plant structures, with sphagnum colonies being particularly affected. Trees in urban areas are recognized as eco-friendly and sustainable tools that can be used to detect and reduce air pollution. However, dust can have detrimental effects on leaf productivity, photosynthesis, and transpiration (Chaudhary and Rathore, 2019). Resilient tree species can promote growth, survival, and environmental benefits (Sjöman et al., 2024). Eucalyptus camaldulensis is native to Australia and is characterized by its rapid growth, drought tolerance, and ability to thrive in various soil types. Its ecological roles include soil stabilization, water management, and habitat provision for wildlife. Due to these attributes, it is frequently used in afforestation and land reclamation projects (Yousaf et al., 2021). Therefore, this study was designed to investigate the growth potential and physiological changes in Eucalyptus camaldulensis under dust pollution.

2. Materials and Methods

A pot experiment was conducted at the Forest Nursery and Experimental Area, Institute of Forest Sciences, The Islamia University of Bahawalpur, Pakistan. The experiment was performed to determine the effects of different types of dust pollution on *Eucalyptus camaldulensis*. Disease-free, uniformly sized six-month-old seedlings of *Eucalyptus camaldulensis* were obtained from the forest nursery and transplanted into pots. Five different types of dust were used for the experiment, and three replicates were maintained for each treatment (Table 1).

2.1. Harvesting and plant analysis

Table 1. Detailed description of different dust treatments (T_1–T_5) used in the pot experiment to evaluate the response of *Eucalyptus camaldulensis* under dust pollution conditions

Treatment	Dust type	Description
T_1	Control	No dust application (clean, unpolluted condition)
T_2	Charcoal dust	Fine particulate dust generated from charcoal combustion
T_3	Wood dust	Dust collected from wood processing and sawing activities
T_4	Soil dust	Fine soil particles collected from agricultural field soil
T_5	Cement dust	Fine particulate dust obtained from cement handling and industrial sources

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At the time of harvest, a digital Vernier caliper was used to measure stem diameter, and a measuring tape was used to record plant height. After measuring the fresh weight of roots and shoots, the samples were dried in an oven at 80°C for 24 hours. Subsequently, dry weights were recorded. Various physiological and biochemical attributes were measured using standardized methods.

2.2. Measurement of chlorophyll contents

Chlorophyll pigment was extracted from leaf discs (0.5 g) after centrifugation at high speed for a few minutes. The extraction process involved soaking the discs in 80% acetone, maintained at 10°C for an extended period. Spectrophotometer readings were taken at 645, 652, 663, and 480 nm to determine the absorbance of the supernatant (PG T60U, Leicestershire, UK). Chlorophyll concentrations were calculated using the following formulas:

Chlorophyll a (mg g^{-1} FW) =

$$\text{Chl a} = \frac{[12.7(\text{OD}_{663}) - 2.69(\text{OD}_{645})] \times \text{V}}{1000 \times \text{W}}$$

Chlorophyll b (mg g^{-1} FW) =

$$\text{Chl b} = \frac{[22.9(\text{OD}_{645}) - 4.68(\text{OD}_{663})] \times V}{1000 \times W}$$

Carotenoid concentration was calculated using absorbance at 470 nm following the method of Wellburn (1994).

2.3. Antioxidant enzymes

Leaf segments (0.5 g) were homogenized with 10 mL extraction buffer consisting of 50 mM phosphate buffer (pH 7.8), 1 g PVP, 1 mM EDTA, and 0.5% Triton X-100. The mixture was maintained at 0–4°C. The homogenate was centrifuged at 12,000 rpm for 20 minutes to obtain the enzyme extract. Peroxidase activity was measured at 470 nm using guaiacol, H_2O_2, and KH_2PO_4 buffer with EDTA (pH 7), while catalase and ascorbate peroxidase activities were measured at 240 nm. Superoxide dismutase activity was determined at 560 nm (Chance and Maehly, 1955; Giannopolitis and Ries, 1977). A spectrophotometer (CE7400, 146-630, England) was used for absorbance readings.

2.4. Determination of total soluble protein

Soluble protein content was measured using the Bradford method (Bradford, 1976). Two milliliters of Bradford reagent were added to a microcentrifuge tube containing 50 µL of sample. The Bradford reagent was used as a blank. Absorbance was measured at 595 nm. Protein concentration was determined using a standard curve of bovine serum albumin.

2.5. Determination of MDA contents

Lipid peroxidation in plant membranes was assessed by measuring malondialdehyde (MDA) content. Fresh leaf extract (0.25 g) was centrifuged at 10,000 rpm for 15 minutes, and MDA levels were determined according to (Olatunde et al., 2021). Absorbance was measured at 532 nm and 600 nm to calculate overall turbidity.

2.6. Statistical analysis

Data was analyzed using Statistics version 8.1 with an appropriate statistical design. Mean comparisons were performed using the Least Significant Difference (LSD) test at $\alpha = 5\%$ ($P \leq 0.05$) (Mead, 2017).

3. Results

3.1. Morphological attributes

Figure 1 demonstrates that pollution had strong inhibitory effects on the overall morphological attributes of *Eucalyptus camaldulensis* plants, leading to a significant decrease ($P \leq 0.05$) in plant growth parameters. *Eucalyptus camaldulensis* plants showed the greatest reduction under charcoal dust treatment compared to the control. The minimum plant height (33.37 ± 1.95 cm), stem diameter (8.14 ± 0.43 mm), and root dry weight (7.52 ± 0.08 g) were observed in plants exposed to charcoal dust, compared to the control, where plant height (65.86 ± 2.56 cm), stem diameter (13.48 ± 0.47 mm), and root dry weight (12.88 ± 0.45 g) were recorded. On the other hand, wood dust slightly decreased plant height (51.80 ± 1.74 cm), stem diameter (10.50 ± 0.79 mm), and root dry weight (8.80 ± 0.46 g) compared to the control. The overall effect of treatments on morphological attributes of *Eucalyptus camaldulensis* followed the order: $T_1 > T_3 > T_4 > T_5 > T_2$.

3.2. Physiological attributes

Data regarding chlorophyll a and chlorophyll b concentrations are shown in (Figure 2). The results indicate that different sources of pollution in the growth medium had a significant ($P \leq 0.05$) adverse effect on physiological characteristics of plants. The control treatment (T_1) showed the highest chlorophyll a (0.94 ± 0.17 mg g^{-1} FW) and chlorophyll b (0.66 ± 0.02 mg g^{-1} FW). In contrast, the lowest chlorophyll a (0.41 ± 0.01 mg g^{-1} FW) and chlorophyll b (0.48 ± 0.01 mg g^{-1} FW) were observed in plants treated with charcoal dust (T_2). Wood dust (T_3) caused a slight reduction in chlorophyll a (0.78 ± 0.04 mg g^{-1} FW) and chlorophyll b (0.56 ± 0.01 mg g^{-1} FW) compared to the control. The treatment effects followed the order: $T_1 > T_3 > T_4 > T_5 > T_2$.

3.3. Protein and MDA content

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Protein concentration and malondialdehyde (MDA) content in *Eucalyptus camaldulensis* plants were significantly affected ($P \leq 0.05$) by different pollution sources in the growth medium (Fig. 3). The maximum protein concentration (2.30 ± 0.07 mg g^{-1} protein) was recorded in the control treatment, while the minimum (0.63 ± 0.02 mg g^{-1} protein) was observed in T_2 (charcoal dust). However, protein concentration was slightly lower in the control (2.30 ± 0.07 mg g^{-1} protein) compared to T_4 (soil dust) (1.76 ± 0.15 mg g^{-1} protein), which appears inconsistent with other results and may need rechecking. The protein content followed the order: $T_1 > T_4 > T_5 > T_3 > T_2$. For MDA content, significant differences ($P \leq 0.05$) were observed among treatments. The maximum MDA content (6.33 ± 0.21 µmol g^{-1} FW) was recorded in T_5 (cement dust), compared to the control (2.40 ± 0.20 µmol g^{-1} FW), while the lowest value (3.66 ± 0.09 µmol g^{-1} FW) was observed in T_2 (charcoal dust). The treatment effect followed the order: $T_5 > T_4 > T_3 > T_2 > T_1$.

3.4. Biochemical attributes

Figure 4 shows the effects of different pollutants on antioxidant enzyme activities in *Eucalyptus camaldulensis*. The results demonstrated that plants grown under polluted conditions exhibited altered antioxidant enzyme activities compared to the control, with the strongest effects observed under charcoal dust treatment. The lowest activities of superoxide dismutase (5.12 ± 0.22 mg^{-1} protein), peroxidase (0.55 ± 0.02 mg^{-1} protein), and catalase (10.14 ± 1.27 mg^{-1} protein) were recorded in the control treatment compared to polluted treatments. Application of charcoal dust increased superoxide dismutase activity (9.68 ± 0.27 mg^{-1} protein). Similarly, higher peroxidase (1.38 ± 0.09 mg^{-1} protein) and catalase (38.17 ± 2.19 mg^{-1} protein) activities were observed in plants exposed to polluted conditions compared to the control. The overall trend of antioxidant enzyme activity was: $T_2 > T_5 > T_4 > T_3 > T_1$.

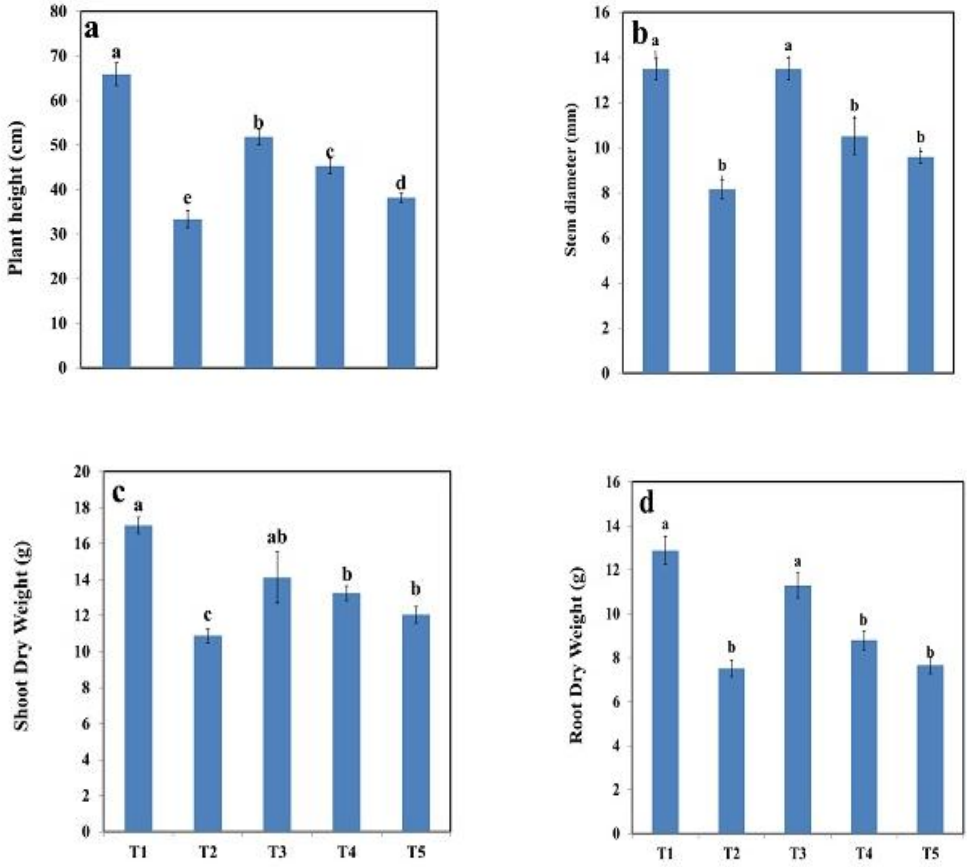


Figure 1. Different morphological characteristics, such as **(**a) plant height (cm), (b) stem diameter (mm), (c) shoot dry weight, (d) root dry weight, of *Eucalyptus camaldulensis* plants were examined in relation to Control (T_1), Charcoal dust (T_2), Wood dust (T_3), Soil dust (T_4) and Cement dust (T_5). The graph illustrates the average values of three repeated measurements. The error bars represent standard deviations, while the letters represent pairwise comparisons that were performed using the LSD test at a significance level of 5% (α=0.05).

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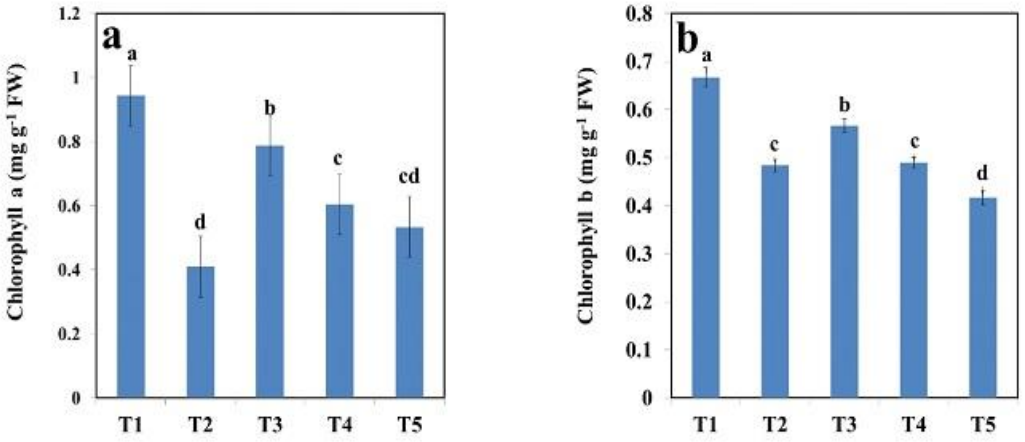


Figure 2. (a) Chlorophyll a (mg.g^{-1} FW) and (b) chlorophyll a (mg.g^{-1} FW) concentrations in *Eucalyptus camaldulensis* plants were examined in relation to Control (T_1), Charcoal dust (T_2), Wood dust (T_3), Soil dust (T_4) and Cement dust (T_5). The graph illustrates the average values of three repeated measurements. The error bars represent standard deviations, while the letters represent pairwise comparisons that were performed using the LSD test at a significance level of 5% (α=0.05).

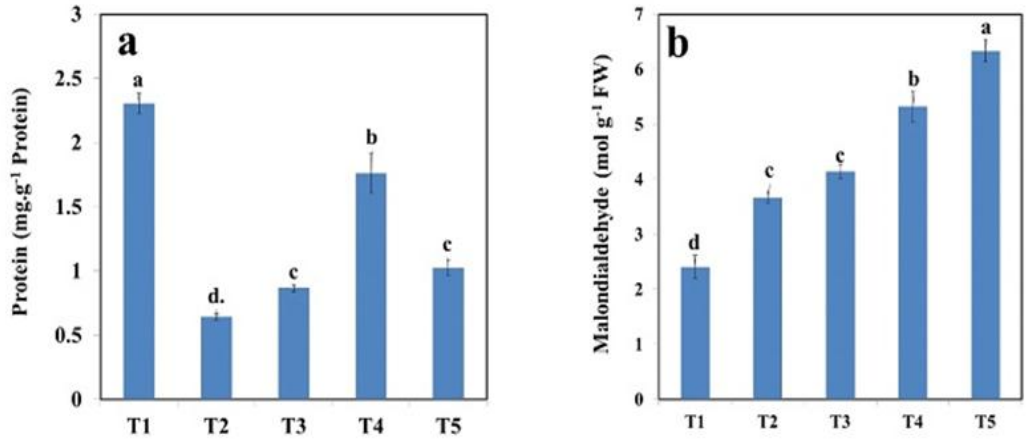


Figure 3. Content of **(**a) **s**oluble protein (mg^{-1} protein) and (b) malondialdehyde (mol g^{-1} FW) in *Eucalyptus camaldulensis* plants examined in relation to Control (T_1), Charcoal dust (T_2), Wood dust (T_3), Soil dust (T_4) and Cement dust (T_5). The graph illustrates the average values of three repeated measurements. The error bars represent standard deviations, while the letters represent pairwise comparisons that were performed using the LSD test at a significance level of 5% (α=0.05).

3.5. Principal Component Analysis (PCA)

To evaluate the effects of different dust types (charcoal, wood, soil, and cement) on growth, biochemical, and antioxidant attributes of *Eucalyptus camaldulensis*, principal component analysis (PCA) was performed. As shown in Fig. 5, the biplot illustrates relationships among measured variables and dust treatments, including cement, charcoal, control, soil, and wood. The first principal component (Dim1) explained 75.6% of the total variation, while the second component (Dim2) explained 12.5%, indicating that most variability was captured by Dim1. The control group (green squares) was positioned on the negative side of Dim1, indicating clear separation from polluted treatments. Cement dust samples (red circles) were widely dispersed, indicating variability within the group. Wood dust (purple pentagons) and charcoal dust (orange triangles) showed closer clustering, indicating higher homogeneity.

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Variables such as stem diameter, SOD, POD, CAT, root length, shoot length, protein, and MDA were strongly influenced by pollution sources, as indicated by vector direction and length. Longer vectors indicate stronger contributions to PCA dimensions. Samples located near specific vectors indicated higher values of those traits.

orientation, surface geometry, pubescence, leaf length, and canopy cover along roadsides (Soheili et al., 2023). Carbon dust, in particular, has a detrimental effect on the morphological, physiological, and biochemical attributes of plants. Dust from roadside vehicles, coal power stations, and other sources damages plant leaves (Swami, 2018). Dust also

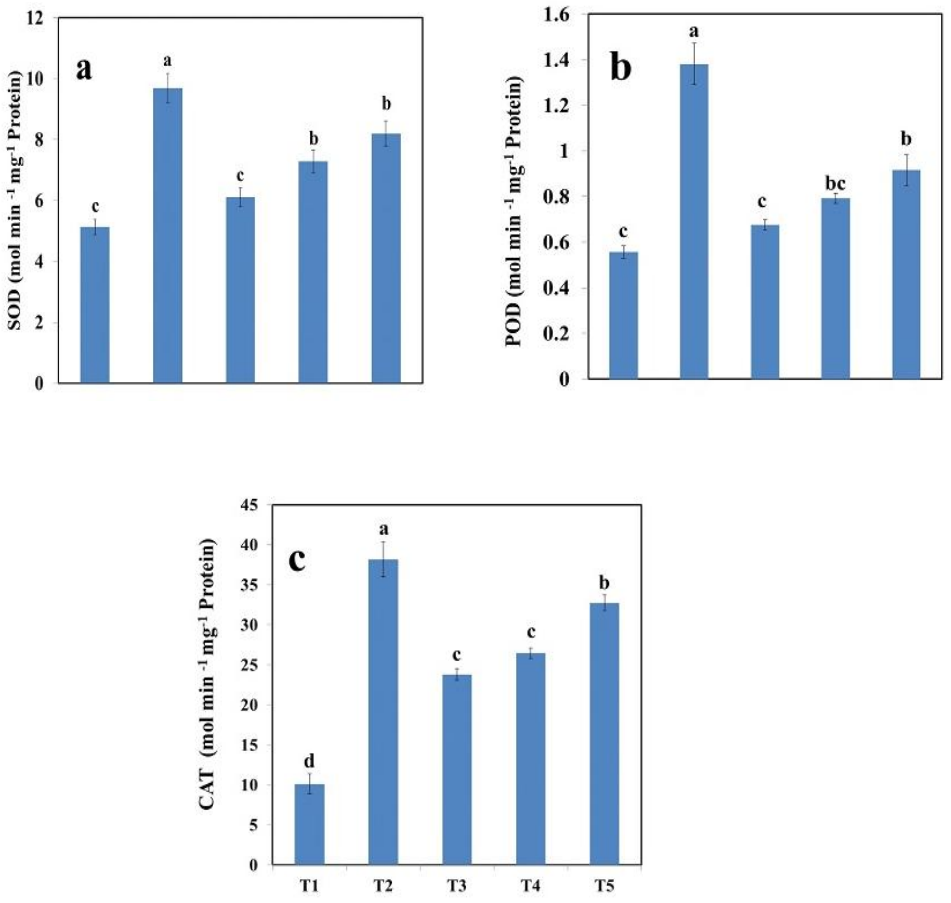


Figure 4. Activities of antioxidant enzymes, such as **(**a) superoxidase activity (mg^{-1} protein), (b) peroxidase activity (mg^{-1} protein) and (c) catalase activity (mg^{-1} protein) in *Eucalyptus camaldulensis* plants were examined in relation to Control (T_1), Charcoal dust (T_2), Wood dust (T_3), Soil dust (T_4) and Cement dust (T_5).The graph illustrates the average values of three repeated measurements. The error bars represent standard deviations, while the letters represent pairwise comparisons that were performed using the LSD test at a significance level of 5% (α=0.05).

4. Discussion

Dust accumulation on tree components slows down chemical reactions and damages cells and chlorophyll content. According to numerous studies, dust pollution limits photosynthesis and damages both tissues and leaves (Ismail et al., 2023). Dust accumulation affects plant species in various ways depending on parameters such as leaf

affects the visible and shortwave infrared reflectance of leaves. Plants may experience changes in light quality and quantity, which ultimately affect photosynthesis (Kour & Adak, 2024). Dust deposition on plant surfaces blocks stomata and limits gas exchange (Kour & Adak, 2024). As a result, growth and biomass decrease due to reduced net photosynthesis and transpiration rates (Mndela et al., 2022). When toxicity levels are high, lipid peroxidation and

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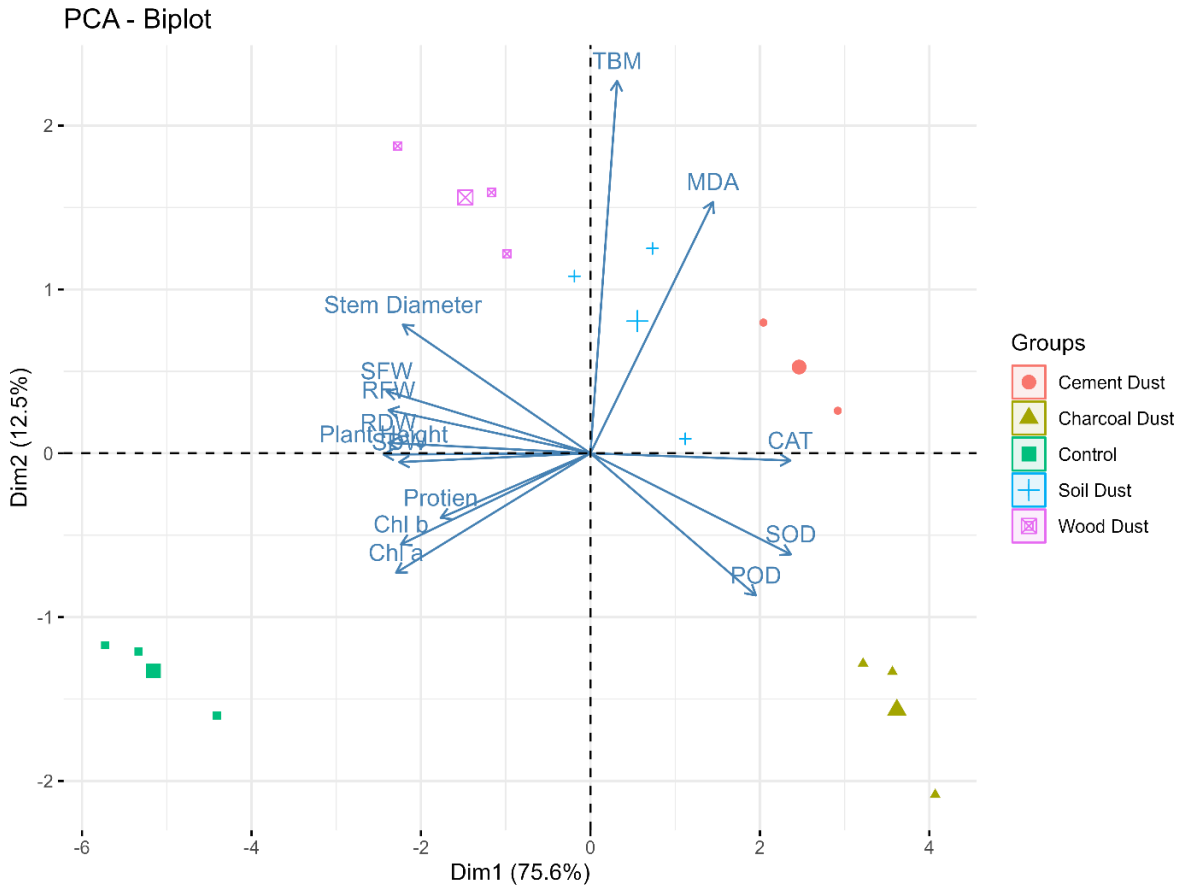


Figure 5. Principal Component Analysis (PCA) was used to evaluate the growth, physiological and biochemical characteristics of *Eucalyptus camaldulensis* in response to several pollution sources, including dust from charcoal, wood, soil and cement. Two plots depicting the relationships between SFW: Chl a, shoot fresh weight, chlorophyll a content and powdered on demand. RFW, RDW, Chl b and catalase represent root fresh weight, root dry weight, root length, chlorophyll b concentration and catalase activity, respectively. Protein, Malondialdehyde, Total Dry Biomass, Shoot Dry Weight, Catalase activity, Superoxide Dismutase activity, etc.

malondialdehyde (MDA) levels increase (Su et al., 2019). Reactive oxygen species (ROS) and lipid peroxidation cause significant cellular damage, including ion loss, DNA degradation, soluble protein breakdown, structural alterations, membrane damage, and cell death. Antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) protect plants against oxidative stress. SOD reduces substrates of the Haber–Weiss reaction, including superoxide radicals, hydrogen peroxide (H_2O_2), and hydroxyl radicals. Hydroxyl radicals can severely damage biological membranes, DNA, and soluble proteins (Wang et al., 2018). CAT enzymes reduce oxidative stress by converting H_2O_2 into water and oxygen. POD enzymes also detoxify H_2O_2, sometimes more effectively than CAT under certain conditions. These enzymes collectively reduce oxidative stress and help maintain cellular function, thereby supporting repair and survival mechanisms (Guo et al., 2018). Thus, plant species increase SOD and POD activity to combat ROS and minimize oxidative damage (Fujita & Hasanuzzaman, 2022). Tomar et al. (2018) demonstrated that ROS are present in cell walls, root systems of germinated seeds, and leaves of young plants. POD, SOD, and CAT enzymes mitigate oxidative stress by regulating reactive oxygen species levels, highlighting their essential role in plant defense. Previous studies indicate that POD enzymes break down H_2O_2 after ascorbate peroxidase activity, converting hydrogen peroxide and hydroperoxides into water or alcohols, thereby reducing cellular toxicity (Sahu et al.,

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2022). Previous experiments have demonstrated that *Bombax ceiba* exhibits higher chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid content. Carbon dust reduces photosynthetic pigments across species (Nawaz et al., 2022). Photosynthesis requires both oxygen and light; however, dust accumulation on leaves blocks stomata and reduces light absorption, thereby limiting gas exchange. This leads to reduced energy capture by the light-harvesting complex and soluble protein efficiency loss (Pan et al., 2020). In conclusion, *Eucalyptus camaldulensis* demonstrates strong growth capacity and adaptive responses to dust pollution. This species tolerates adverse conditions and can contribute to reducing dust pollution. It effectively traps dust particles, thereby improving air quality and providing an environmentally friendly response to pollution. Adaptive changes such as variations in leaf morphology and growth patterns reflect their resilience. These findings have important implications for environmental conservation, urban sustainability, and reforestation. The growth and adaptation of *Eucalyptus camaldulensis* may contribute to the development of healthier and more sustainable ecosystems in the context of pollution and climate change challenges.

5. Conclusion

This study demonstrated that dust pollution has a significant negative impact on the morphological, physiological, and biochemical attributes of *Eucalyptus camaldulensis*. Among all treatments, charcoal dust exhibited the most severe inhibitory effects on plant growth, chlorophyll content, and antioxidant enzyme activity, while control plants showed optimal performance. Increased levels of oxidative stress markers, such as malondialdehyde (MDA), further confirmed cellular damage under dust exposure, whereas changes in antioxidant enzyme activities indicated the activation of defense mechanisms in response to stress. Overall, *Eucalyptus camaldulensis* showed a considerable degree of tolerance to dust stress, highlighting its potential role in mitigating dust pollution in affected environments. Its ability to trap airborne particles and maintain physiological stability under stress conditions suggests that it can be effectively utilized in afforestation, urban plantations, and environmental restoration programs. These findings support the use of *Eucalyptus camaldulensis* as a promising species for improving air quality and contributing to sustainable ecosystem management in dust-polluted areas.

6. Funding

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7. Acknowledgment

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8. Conflict of Interest

The authors declare no conflict of interest.

9. Authors' Contribution

Aneeqa Sarfraz, Muhammad Azeem Sabir, and Tanveer Hussain Khan contributed to the conceptualization, experimental design, data collection, and initial drafting of the manuscript. Fahad Rasheed and Hafiz Muhammad Furqan Shaheen assisted in data analysis, interpretation of results, and critical revision of the manuscript. Muhammad Talha Bin Yousaf and Shahid Ali Khan supervised the research work, provided technical guidance, and contributed to manuscript review, editing, and final approval. All authors have read and approved the final version of the manuscript.

10. SDGs Addressed

This study addresses Sustainable Development Goal (SDG) 13: Climate Action and SDG 15: Life on Land by highlighting the role of *Eucalyptus camaldulensis* in mitigating dust pollution, improving air quality, and supporting ecosystem restoration and sustainable land management.

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