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Desert Dust Deposition: Impacts on Physiological Responses, Chlorophyll Pigments, and Stomatal Conductance in Wheat and Cowpea

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ABSTRACT

Deposition of dust particles on plant leaves reduces light interception. Additionally, dust accumulation in stomata decreases gas exchange in leaves. The effects of dust deposition following sand and dust storms (SDS) are critical, and the physiological responses of plants to dust deposition as an abiotic stress factor are of primary importance. We hypothesized that dust storm occurrence negatively affects leaf traits in wheat (*Triticum aestivum L.*) and cowpea (*Vigna unguiculata L.*). The effects of desert dust on photosynthetic pigment contents and stomatal conductance were studied in both species. Wheat and cowpea plants were subjected to dust treatments in a factorial layout based on a randomized complete block design in Dezful and Mashhad. Experimental treatments included desert dust concentration (0, 500, and 1500 μg m^{-3}), number of dust applications (once, twice, thrice), and dust type (samples collected during dust storms in Dezful and Zabol, two of the most dust-prone regions of Iran). Dust application reduced stomatal conductance in both plants at both locations. Increasing dust concentration reduced chlorophyll a+b, a, and b in wheat leaves, while only chlorophyll b in cowpea leaves was significantly affected. Overall, this study provides new insights into how desert dust affects photosynthetic pigments and stomatal conductance in wheat and cowpea through shading and stomatal occlusion during dust storms.

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1. Introduction

Transportation of dust particles in the atmosphere is a natural phenomenon (Griffin *et al*., 2001; Al-Hemoud *et al*., 2022). Any type of dust that enters the atmosphere, whether from natural events or human activities, is eventually deposited elsewhere (Armbrust, 1986; Al-Dousari *et al*., 2018; Liang *et al*., 2022). Severe dust storms have the capacity to transport millions of tons of soil across the globe (Griffin *et al*., 2001; Doronzo *et al*., 2016; Al-Hemoud *et al*., 2022).

Iran is both a source of dust and a recipient of dust originating from other regions. Dust storms commonly occur in deserts during the warm seasons in countries such as Iran, Iraq, Saudi Arabia, and Pakistan. In recent years, desertification and human activities have caused the desiccation of lakes and wetlands, leading to the transport of large quantities of soil from Turkmenistan, Afghanistan, Iraq, Syria, and Saudi Arabia. These events have resulted in severe air pollution over extended areas of Iran (Rashki *et al*., 2014; Boroughani *et al*., 2022). Sand and dust storms impose substantial on-site and off-site costs on the environment and agriculture (Gholizadeh *et al*., 2021). They can reduce soil fertility, directly cause crop losses, and consequently lead to significant economic damage (Wang *et al*., 2006; Al-Dousari *et al*., 2020; Omara *et al*., 2020).

Several studies have reported that the deposition of dust can reduce chlorophyll content in Green-gram (Phaseolus aureus) (Prasad and Rao, 1981), Wheat (Triticum aestivum L.) (Singh and Rao, 1981), and Olive (Olea europaea L.) (Nanos and Ilias, 2007). Dust application has also been shown to reduce stomatal conductance in Cotton (Gossypium hirsutum L., Xinluzhong-21) (Zia-Khan *et al*., 2015) and Mangrove (Avicennia marina) (Naidoo and Chirkoot, 2004). Moreover, significant reductions in plant height were observed in Cowpea (Vigna unguiculata L.) (Hatami *et al*., 2018; Chauhan and Joshi, 2010) and Mustard (Brassica campestris L.) (Chauhan and Joshi, 2010). Yield reductions due to dust application have been reported for Cowpea (Vigna unguiculata L.) (Hatami *et al*., 2018), Wheat (Triticum aestivum) (Hatami *et al*., 2017; Boroughani *et al*., 2022), Cotton (Gossypium hirsutum L., Xinluzhong-21) (Zia-Khan *et al*., 2015), and Brassica campestris L. var. G-S20 (Shukla *et al*., 1990).

In this study, a narrow-leaf plant and a broad-leaf plant were selected to investigate their responses to dust deposition. Wheat (Triticum aestivum) was chosen as the narrow-leaf plant due to its critical economic importance and role in food supply. Wheat can be produced even in regions where climatic conditions or drought limit the cultivation of other crops (Khodabandeh, 1998). Cowpea (Vigna unguiculata L.), a broad-leaf plant, was chosen as it is an important source of protein and carbohydrates. The main aim of this study was to determine whether desert dust adversely affects chlorophyll content and stomatal conductance in wheat and cowpea.

2. Materials and methods

2.1. Site characteristics

Field trials were conducted at the research farms in Dezful (32°20'N, 48°30'E; 143 m altitude) and at Ferdowsi University of Mashhad (36°15'N, 56°28'E; 985 m altitude) (Fig. 1). The physical and chemical properties of the field soils at both sites were measured and are presented in Table 1. Meteorological data for the study period are shown in Fig. 2. The number of dust days per month in Dezful and Mashhad during the study period is illustrated in Fig. 3.

2.2. Treatments, experimental design, and management

All experimental fields were arranged in a factorial layout based on a randomized complete block design with three replications. The experiments included three factors: desert dust concentration, number of dust applications, and types of desert dust.

Desert dust concentration was applied at three levels: 0, 500, and 1500 µg m^{-3}. A concentration of 500 µg m^{-3} was selected as the minimum harmful dust level (Rashki *et al*., 2012; Shahsavani *et al*., 2012), while 1500 µg m^{-3} represented a very high dust concentration that naturally occurs in Dezful and Zabol. The number of dust applications was set at once, twice, or three times. The third factor, type of desert dust, included two sources: dust collected from Dezful and dust collected from Zabol.

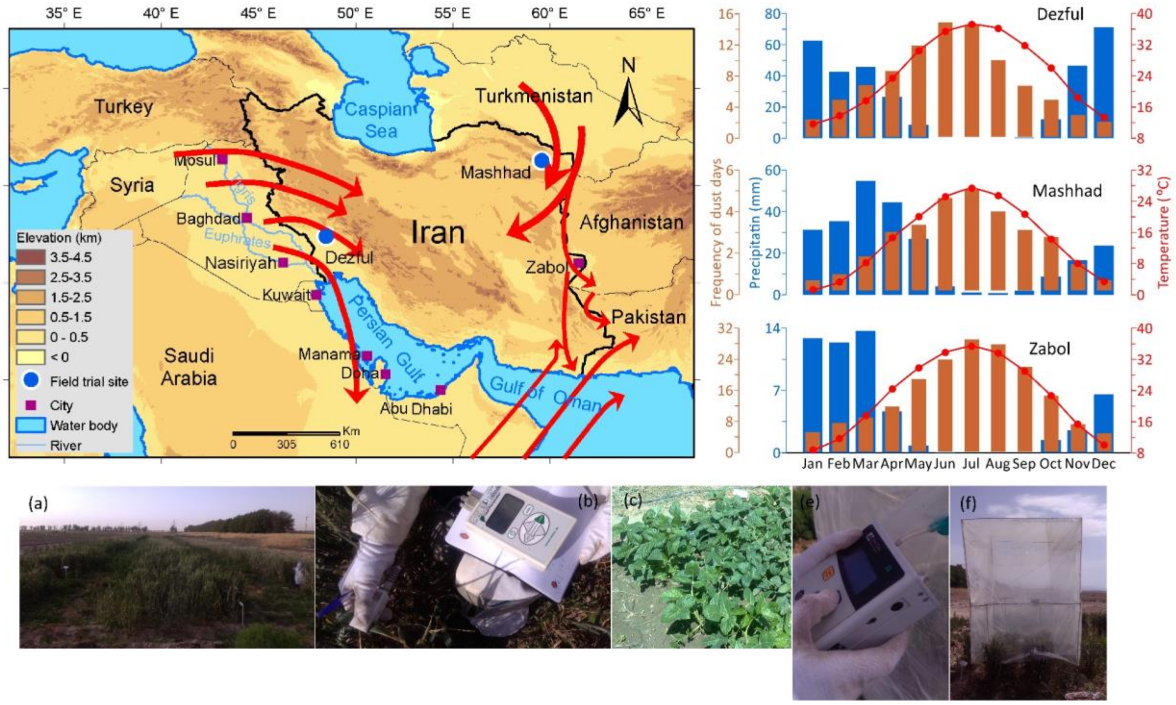

Fig. 1. Location map for the study areas: Dezful and Mashhad located in South-West and North-East of Iran, respectively. Red arrow line shows dust path sources to the study areas.(a) the wheat farm, (b) Stomatal conductance (gs) measurement using a portable leaf porometer (SC-1; Decagon devices), (c) the Cowpea farm, (e) measurement of chlorophyll ‘a’ and ‘b’ , (f) mobile chambers with a cross section of 1 × 1.5 m and a height of 2 m for dust application

Table.1. Physical and chemical properties of soil (0-30 cm depth) at the study sites during the study periods

Location	Electrical conductivity (µs.m^{-1})[1]	Acidity	Total nitrogen (%)	Organic matter (%)	Available phosphorous (mg.kg^{-1})	Available potassium (mg.kg^{-1})	Soil texture
Mashhad	640	7.65	0.067	0.67	14	325	Silty loam
Dezful	720	7.26	0.077	0.78	11.76	129	Silty clay loam

[1] - Micro Siemens per meter

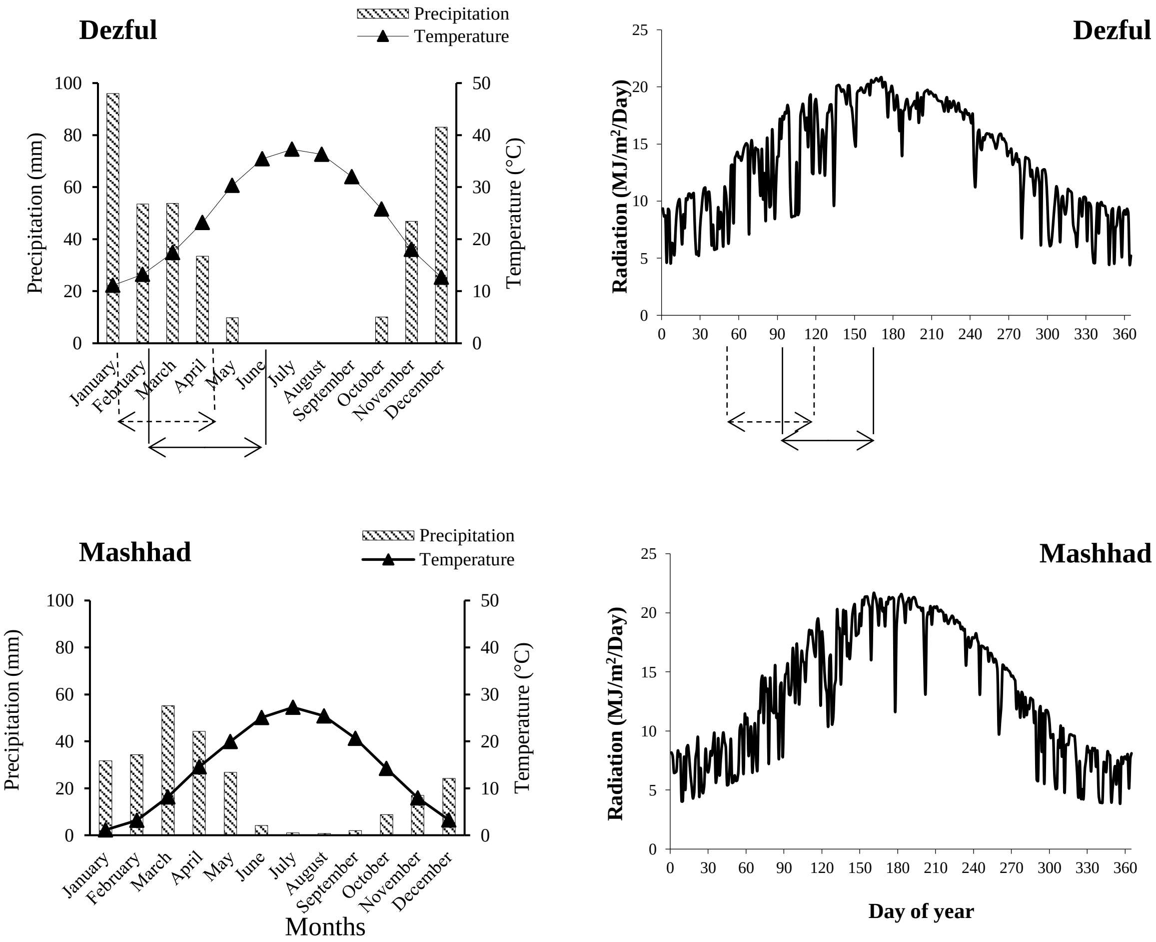

Fig. 2. Meteorological conditions at the study sites for On the left, mean monthly temperature and precipitation values for the study sites. <--> and ⟷ demonstrate sowing to harvest for wheat and cowpea, respectively. On the right, daily solar radiation at the study sites. Source: I.R. OF IRAN Meteorological Organization

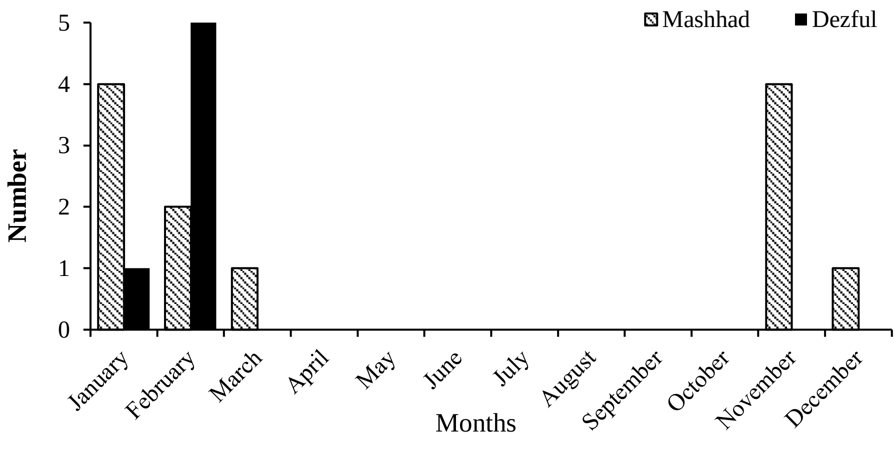

Fig. 3. The monthly number of dust storms for the study sites. Source: I.R. OF IRAN Meteorological

Organization.

At both locations, separate experiments were conducted on Wheat (*Triticum aestivum L.*) and Cowpea (*Vigna unguiculata L.*). Plot size was 2 × 2 m, with a distance of 0.5 m between plots and 1.5 m between replicates for both crops. Conventional tillage was performed prior to sowing. Wheat seeds were sown at a rate of 150 kg ha^{-1} on ridges spaced 25 cm apart in both Dezful and Mashhad. Cowpea seeds were sown at 20 plants m^{-2} on ridges with a spacing of 50 × 10 cm.

2.3. Dust sampling and compositional analysis

Dust samples were collected during heavy desert dust storms in Zabol and Dezful. In Zabol, during the dust-storm events in 2013 and 2014, samples of airborne dust were collected by the method descript by (Rashki *et al.*, 2012). These samples were mixed and was used for dust treatments of this study. . In Dezful, dust was collected using outdoor traps placed to capture airborne particles during a dust storm. The collected dust samples were sent to the Stoneman Laboratory (Geology Department) at the University of Pretoria, South Africa, for major and trace elements analysis by applying X-ray Fluorescence (XRF) techniques and for compositional analysis. The results of this analysis are presented in Table 2.

Table 2. Chemical components of dust samples used in this study (%)

Dust source	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	NiO	V_2O_5	ZrO_2	CuO	LOI	TOTAL
Dezful	31.60	0.44	5.89	4.16	0.06	4.73	23.30	1.11	0.32	0.14	0.03	0.01	0.01	0.02	0.00	27.78	99.60
Zabol	46.7	0.62	10.45	4.15	0.09	3.72	12.77	3.19	0.02	0.19	<0.01	<0.01	<0.01	<0.01	<0.01	19.1	99.8

2.4. Performance of dust treatment

Dust application was carried out using mobile chambers with a cross-section of 1 × 1.5 m and a height of 2 m. Dust particles were delivered into the chambers using a blower, and a portable dust concentration monitoring instrument (TSI® Track) was used to ensure accurate control of dust levels during application.

Dust applications were scheduled according to the growth stages of the plants. For wheat, applications were timed at tillering, booting, and milk stages. Specifically:

- Once application: tillering stage
- Twice application: tillering and booting stages
- Thrice application: tillering, booting, and milk stages

For cowpea, applications were timed at canopy closure, flowering, and pod formation stages:

- Once application: canopy closure stage
- Twice application: canopy closure and flowering stages
- Thrice application: canopy closure, flowering, and pod formation stages

Plant growth stages were determined when 50% of the plants in a plot reached a specific stage. During all dust applications and the subsequent period, no rainfall or natural dust storms occurred in any of the study areas.

2.5. Data collection: Stomatal conductance and Chlorophyll content

Stomatal conductance (g_s) was measured using a portable leaf porometer (SC-1; Decagon

Devices). Measurements were conducted two days after each dust application, resulting in three measurements per plot for both wheat and cowpea at both locations. Measurements were taken on the abaxial side of three fully developed, randomly selected leaves per plot. The instrument was calibrated before each measurement following the manufacturer's instructions.

In order to measure chlorophyll, green tissue samples were taken one week before harvest in both Dezful and Mashhad regions for wheat plants from the flag leaf and for cowpeas from the third developed leaf from the top of the plant. Chlorophyll 'a' and 'b' concentrations (µg g^{-1} fresh leaf) were determined according to the formula described by Lichtenthaler (1987).

2.6. Statistical analysis

Data were analyzed using analysis of variance (ANOVA) in the Statistical Analysis System (SAS, ver. 9.1). Means were compared using Duncan's multiple range test at $p \leq 0.05$. Graphs were plotted using Microsoft Excel.

3. Results

3.1. Wheat

3.1.1. Chlorophyll

Chlorophyll a+b content in wheat was significantly affected by dust concentration (Table 3). Increasing dust concentrations reduced chlorophyll a+b content at both locations. In Dezful, both 500 and 1500 µg m^{-3} dust concentrations caused a significant reduction compared with the control, while in Mashhad, only the highest concentration (1500 µg m^{-3}) led to a significant decrease. In Dezful, chlorophyll a+b content in the 1500 µg m^{-3} treatment was significantly lower than in the 500 µg m^{-3} treatment (Table 4).

Increasing the number of dust applications also reduced chlorophyll a+b content compared with the control in both locations (Tables 3 and 4). In Mashhad, the interaction between dust concentration and the number of applications was significant. The lowest chlorophyll a+b content was observed with three applications at 1500 µg m^{-3}, which was 28.66% lower than the control (data not shown).

Table 3. ANOVA table showing p values (probability of non- significant effects) for chlorophyll a, b and a+b content of wheat leaf as affected by dust concentration, number of dust application and kind of dust, in Dezful, and Mashhad.

	Dezful			Mashhad		
	Chlorophyll a	Chlorophyll b	Chlorophyll a+b	Chlorophyll a	Chlorophyll b	Chlorophyll a+b
Replication (R)	0.519	0.797	0.493	0.454	0.097	0.251
Dust concentration (A)	**0.000 *****	**0.000 *****	**0.000 *****	**0.000 *****	**0.000 *****	**0.000 *****
No. of dust application (B)	0.058	0.131	**0.030***	**0.008****	**0.003****	**0.000 *****
Kind of dust (C)	0.329	0.395	0.389	0.094	0.479	0.140
A×B	0.215	0.627	0.146	0.097	0.068	**0.039***
A×C	0.784	0.712	0.825	0.208	0.878	0.249
B×C	0.988	0.718	0.984	0.971	0.690	0.939
A×B×C	1.000	0.846	1.000	0.988	0.962	0.984

*Statistically significant (P < 0.05); **statistically significant (P < 0.01); ***statistically significant (P < 0.001).

Table 4. Mean comparison of the effect of dust concentration, number of dust application and kind of dust on chlorophyll a, b and a+b content (μg.g^{-1} fresh leaf) of wheat leaf, in Dezful, and Mashhad

	Dezful			Mashhad		
	Chlorophyll a	Chlorophyll b	Chlorophyll a+b	Chlorophyll a	Chlorophyll b	Chlorophyll a+b
Dust concentration						
Control	748.00a	139.33a	887.33a	751.00a	127.67a	878.67a
500 μg.m^{-3}	634.33b	132.50a	766.83b	730.44a	122.67a	853.11a
1500 μg.m^{-3}	509.33c	69.22b	578.56c	552.56b	105.78b	658.33b
No. of dust application						
Once	685.61a	119.06a	804.67a	718.11a	128.50a	846.61a
Twice	615.28a	114.56a	729.83ab	665.17b	118.22ab	783.39b
Thrice	590.78a	107.44a	698.22b	650.72b	109.39b	760.11b
Kind of dust						
Dezful	646.52a	111.70a	758.22a	692.85a	117.19a	810.04a
Zabol	614.59a	115.67a	730.26	663.15a	120.22a	783.37a

Means with similar letters in each studied factor in each column show non-significant differences according to Duncan's Multiple Range Test at 5% level of probability.

3.1.2. Stomatal Conductance

Stomatal conductance of wheat leaves at the first measurement stage (tillering) was significantly affected by dust concentration in Dezful but not in Mashhad (Table 5). In Dezful, both 500 and 1500 μg m^{-3} concentrations significantly decreased stomatal conductance compared with the control (15.3% and 35.7%, respectively), and the difference between the two concentrations was significant (Table 6).

Table 5. ANOVA table showing p values (probability of non- significant effects) for stomatal conductance in the first, second and third stage of measurement (tillering, booting and milk stages) in wheat leaf as affected by dust concentration, the number of dust application and kind of dust, in Dezfu, and Mashhad.

	Stomatal conductance in Dezful			Stomatal conductance in Mashhad		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Replication (R)	0.449	0.822	0.427	0.369	0.124	0.089
Dust concentration (A)	**0.000 *** **	**0.000 *** **	**0.000 *** **	0.146	**0.000 *** **	**0.000 *** **
No. of dust application (B)	0.613	**0.011***	**0.017***	0.271	**0.039***	**0.024***
Kind of dust (C)	0.525	0.157	0.718	0.809	0.425	0.606
A×B	0.537	0.264	0.256	0.494	0.454	0.080
A×C	0.728	0.178	0.344	0.973	0.734	0.926
B×C	0.582	0.244	0.888	0.606	0.891	0.053
A×B×C	0.791	0.707	0.280	0.553	0.966	0.407

*Statistically significant (P < 0.05); **statistically significant (P < 0.01); ***statistically significant (P < 0.001).

Table 6. Mean comparison of the effect of dust concentration, the number of dust application and kind of dust on stomatal conductance (mmol.$m^{-2}.s^{-1}$) in the first, second and third stage of measurement (tillering, booting and milk stages) in wheat leaf, in Dezful, and Mashhad.

	Stomatal conductance in Dezful			Stomatal conductance in Mashhad		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Dust						
Control	43.03a	37.50a	29.47a	51.23a	37.90a	27.53a
500 µg.m^{-3}	36.44b	26.70b	24.44b	48.41a	23.64b	21.98b
1500 µg.m^{-3}	27.67c	18.78c	21.10c	49.30a	19.69c	21.63b
No. of dust						
Once	36.03a	28.93a	25.74a	48.54a	28.58a	24.18a
Twice	35.84a	27.19b	25.74a	50.89a	26.35b	24.66a
Thrice	35.27a	26.86b	23.53b	49.51a	26.31b	22.30b
Kind of dust						
Dezful	35.92a	27.25a	25.13a	49.79a	26.76a	23.90a
Zabol	35.22a	28.07a	24.88a	49.50a	27.40a	23.53a

Means with similar letters in each studied factor in each column show non-significant differences according to Duncan's Multiple Range Test at 5% level of probability.

At the second measurement stage (booting), dust concentration and the number of dust applications significantly affected stomatal conductance in both locations (Table 5). In Dezful, 500 and 1500 µg m^{-3} concentrations reduced stomatal conductance by 28.8% and 49.9%, respectively, compared with the control, while in Mashhad the reductions were 37.6% and 48.0%, respectively (Table 6). Differences between the two concentrations were significant in both locations. Increasing the number of applications further reduced stomatal conductance, with the greatest reductions observed for two and three applications at 1500 µg m^{-3}: 53.79% and 51.20% in Dezful, and 50.26% and 51.77% in Mashhad (data not shown). Similar values between the second and third stages at the highest concentration are consistent with the time-dependent application schedule (Table 6).

At the third measurement stage (milk stage), stomatal conductance was significantly reduced by both 500 and 1500 µg m^{-3} compared with the control (Dezful: 17.1% and 28.4%; Mashhad: 20.2% and 21.4%, respectively). In Dezful, the difference between the two concentrations was significant, whereas in Mashhad it was not (Table 6). Increasing the number of dust applications continued to reduce stomatal conductance in both locations (Table 6).

3.2. Cowpea

3.2.1 Chlorophyll

The results showed that only chlorophyll b content was significantly affected by dust concentration at both locations, while none of the treatments significantly affected chlorophyll a or total chlorophyll (a+b) content in cowpea leaves (Table 7). Both 500 and 1500 µg m^{-3} dust concentrations reduced chlorophyll b content by 19.95% and 20.85% in Dezful, and 21.10% and 24.67% in Mashhad, respectively, compared with the control (Table 8). There was no significant difference between the effects of 500 and 1500 µg m^{-3} dust concentrations on chlorophyll b content at either location (Table 8).

Although the effects on chlorophyll a+b content were not statistically significant, total chlorophyll content of cowpea leaves tended to decrease with increasing dust concentrations at both locations (Table 8).

Table 7. ANOVA table showing p values (probability of non- significant effects) for chlorophyll a, b, and a+b in cowpea leaf as affected by dust concentration, number of dust application and kind of dust, in Dezful, and Mashhad.

	Dezful			Mashhad		
	Chlorophyll a	Chlorophyll b	Chlorophyll a+b	Chlorophyll a	Chlorophyll b	Chlorophyll a+b
Replication (R)	0.361	0.793	0.308	0.680	0.610	0.709
Dust concentration (A)	0.565	**0.000*** **	0.385	0.270	**0.000*** **	0.052
No. of dust application (B)	0.591	0.473	0.399	0.453	0.885	0.433
Kind of dust (C)	0.130	0.762	0.228	0.952	0.765	0.982
A×B	0.758	0.931	0.694	0.744	0.205	0.817
A×C	0.489	0.968	0.640	0.999	0.963	1.000
B×C	0.608	0.661	0.664	0.805	0.972	0.804
A×B×C	0.383	0.970	0.546	0.907	0.974	0.930

*Statistically significant (P < 0.05); **statistically significant (P < 0.01); ***statistically significant (P < 0.001).

Table 8. Mean comparison of the effect of dust concentration, number of dust application and kind of dust on chlorophyll a, b and a+b content (µg/g^{-1} fresh leaf) of cowpea leaf, in Dezful, and Mashhad

	Dezful			Mashhad		
	Chlorophyll a	Chlorophyll b	Chlorophyll a+b	Chlorophyll a	Chlorophyll b	Chlorophyll a+b
Dust concentration						
Control	679.00a	142.00a	821.00a	717.30a	143.00a	860.00a
500 µg.m^{-3}	693.72a	113.67b	807.39a	672.50a	112.83b	785.33a
1500 µg.m^{-3}	687.06a	112.39b	779.44a	652.61a	107.72b	760.33a
No. of dust application						
Once	690.17a	127.28a	817.44a	707.72a	122.22a	829.94a
Twice	691.17a	122.06a	813.22a	656.78a	119.78a	776.56a
Thrice	678.44a	118.72a	797.17a	677.94a	121.56a	799.50a
Kind of dust						
Dezful	695.26a	121.81a	817.07a	679.81a	121.81a	801.63a
Zabol	677.93a	123.56a	801.48a	681.81a	120.56a	802.37

Means with similar letters in each studied factor in each column show non-significant differences according to Duncan’s Multiple Range Test at 5% level of probability.

3.2.2 Stomatal Conductance

At the first measurement stage (canopy closure), stomatal conductance of cowpea leaves was significantly affected by dust concentration in both locations (Table 9). In Dezful, 500 and 1500 µg m⁻³ dust concentrations reduced stomatal conductance by 14.2% and 33.9%, respectively, while in Mashhad the reductions were 10.8% and 23.2%, respectively, compared with the control. Stomatal conductance under 1500 µg m⁻³ dust concentration was significantly lower than under 500 µg m⁻³ in both locations (Table 10).

Table 9. ANOVA table showing p values (probability of non- significant effects) for stomatal conductance in the first, second and third stage of measurement (canopy closure, flowering, and pod formation stages) in cowpea leaf as affected by dust concentration, number of dust application and kind of dust, in Dezful, and Mashhad.

	Stomatal conductance in Dezful			Stomatal conductance in Mashhad		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Replication (R)	0.129	0.262	0.347	0.475	0.236	0.435
Dust concentration (A)	**0.000*** **	**0.000*** **	**0.005** **	**0.000*** **	**0.000*** **	**0.000*** **
No. of dust application (B)	0.113	**0.003** **	0.246	0.819	**0.003** **	**0.027***
Kind of dust (C)	0.060	0.446	0.357	0.371	0.714	0.848
A×B	0.543	0.073	0.794	0.356	0.083	0.103
A×C	0.200	0.573	0.658	0.385	0.670	0.990
B×C	0.264	0.950	0.990	0.944	0.972	0.377
A×B×C	0.527	0.875	0.999	0.979	0.862	0.681

*Statistically significant (P < 0.05); **statistically significant (P < 0.01); ***statistically significant (P < 0.001).

Table 10. Mean comparison of the effect of dust concentration, number of dust application and kind of dust on stomatal conductance (mmol.m^{-2}.s^{-1}) in the first, second and third stage of measurement (canopy closure, flowering, and pod formation stages) in cowpea leaf, in Dezful, and Mashhad.

	Stomatal conductance in Dezful			Stomatal conductance in Mashhad		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Dust concentration						
Control	48.10a	31.06a	24.07a	49.93a	31.68a	25.95a
500 µg.m^{-3}	41.26b	22.67b	20.18b	44.53b	23.13b	21.25b
1500 µg.m^{-3}	31.78c	20.93c	21.16b	38.33c	21.29c	18.55c
No. of dust application						
Once	39.70a	26.08a	22.56a	43.70a	26.60a	22.98a
Twice	41.52a	24.25b	22.13a	44.85a	24.80b	22.92a
Thrice	39.96a	24.32b	20.71a	44.26a	24.70b	19.85b
Kind of dust						
Dezful	41.11a	25.06a	21.37a	44.94a	25.28a	21.82a
Zabol	39.67a	24.71a	22.23a	43.60a	25.45a	22.01a

Means with similar letters in each studied factor in each column show non-significant differences according to Duncan's Multiple Range Test at 5% level of probability.

At the second measurement stage (flowering), 500 and 1500 µg m⁻³ dust concentrations caused significant reductions in stomatal conductance in Dezful (27.0% and 32.6%, respectively) and Mashhad (27.0% and 32.8%, respectively) relative to the control (Table 10).

The 1500 µg m⁻³ concentration consistently caused significantly lower stomatal conductance than 500 µg m⁻³ at both sites. In addition, stomatal conductance decreased with increasing numbers of dust applications (Table 10).

At the third measurement stage (pod formation), both 500 and 1500 µg m⁻³ dust concentrations significantly reduced stomatal conductance in Dezful (16.2% and 12.1%, respectively) and Mashhad (18.1% and 28.5%, respectively) compared with the control (Table 10). The difference between the 500 and 1500 µg m⁻³ treatments was significant in Mashhad but not in Dezful. Increasing the number of dust applications also caused a significant reduction in stomatal conductance of cowpea leaves at both locations (Table 10).

3.3 Integrated Visualization of Results

To examine the effect of experimental treatments on leaf chlorophyll content, three complementary graphical representations were used. The correlation heat map (Figure 4) showed the overall relationships between experimental treatments and chlorophyll values in the two species and two locations, revealing patterns of correlation between chlorophyll indices. The multiple heat maps (Figure 5) presented the effect of dust concentration and frequency on chlorophyll a, b, and a+b values, disaggregated by species, location, and dust source, allowing for more accurate comparisons of responses. Finally, the standardized Z-score heat map (Figure 6) integrated patterns of relative chlorophyll variation across measurements, with values above and below the mean highlighted in red and blue, facilitating comparisons between indices.

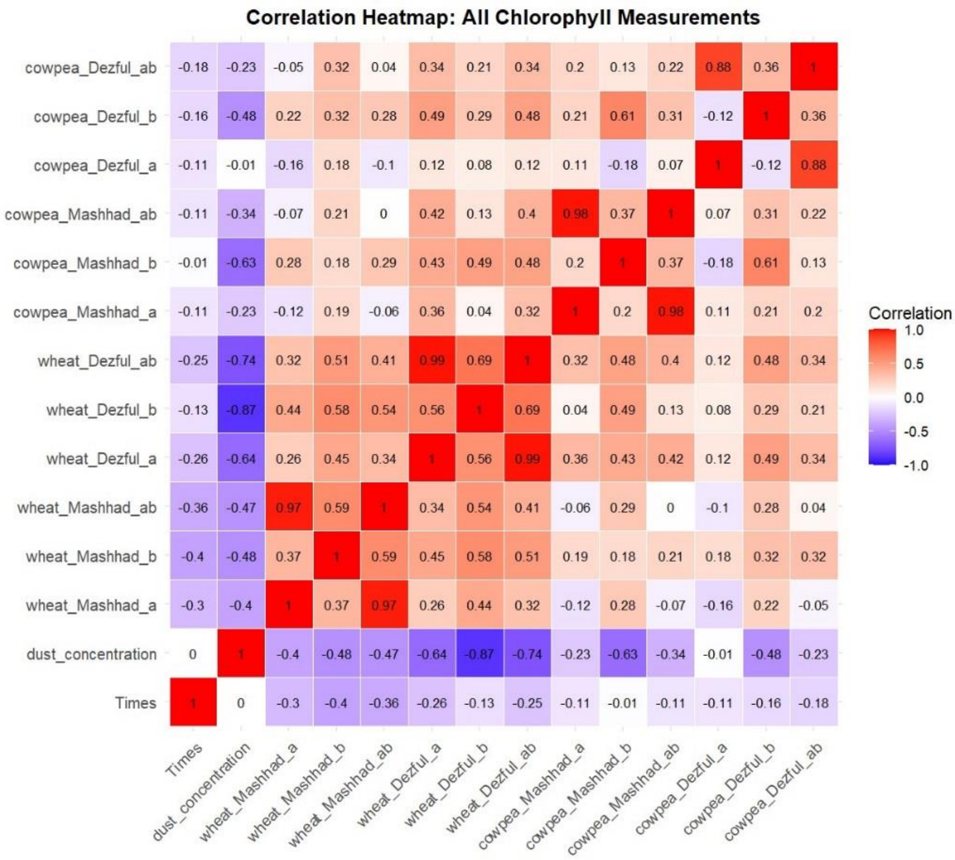

Fig. 4. Correlation Heatmap between experimental treatments and different leaf chlorophyll values in both plant species and two study locations. The intensity and direction of the correlations are indicated by the color spectrum.

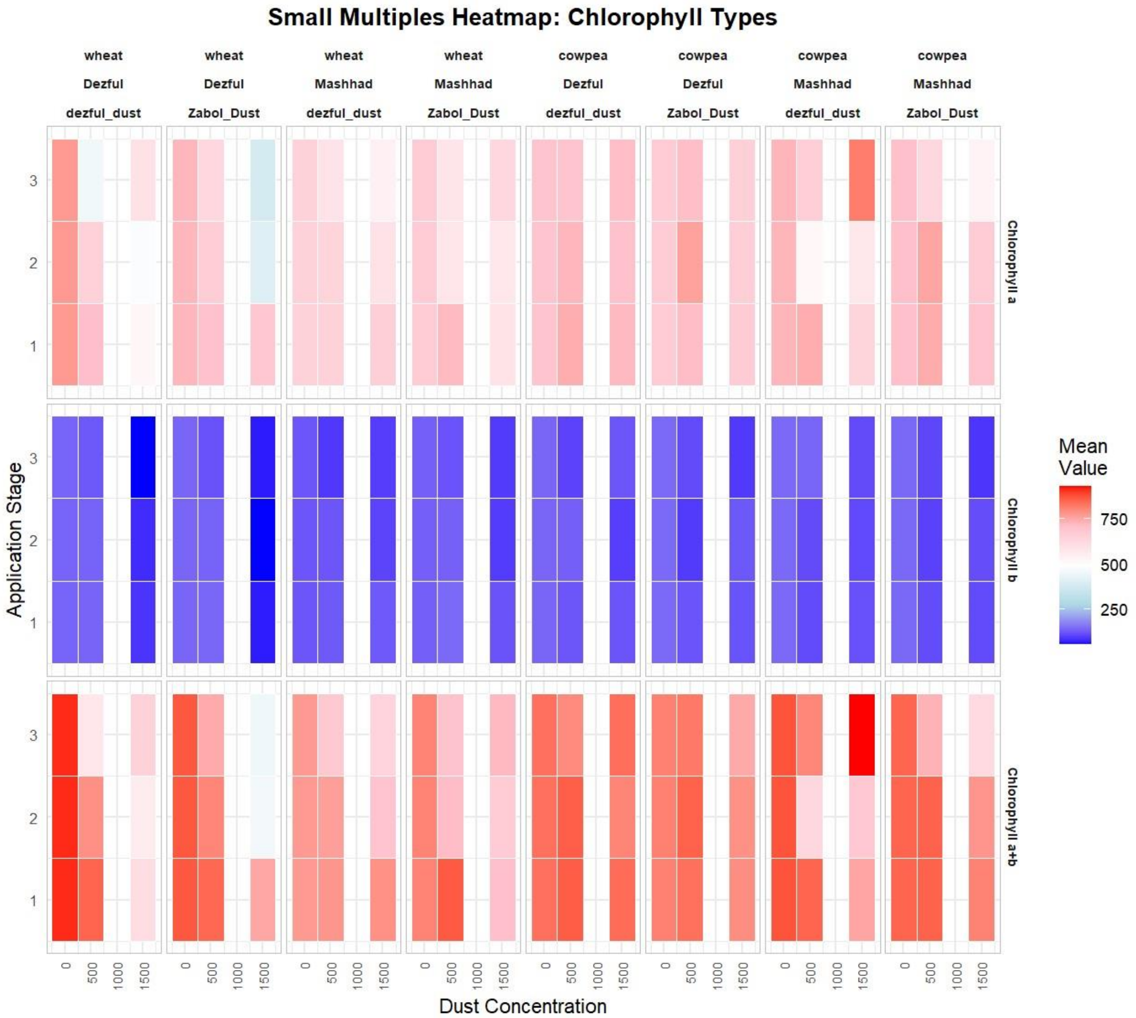

Fig. 5. Small Multiple Heatmap of the effect of dust concentration and dust application frequency on chlorophyll a, b, and a+b values in both plant species and two study locations, with dust type separated by different sources.

In order to comprehensively explain the stomatal conductance response of plants to different dust treatments, a combination of complementary graphical representations was used. The alluvial plot (Fig. 7) revealed the structural and flow-oriented relationships between the experimental factors and the different levels of stomatal conductance. Then, the overall changes in the plant response were examined in the form of mean and standard deviation (Fig. 8) and the statistical distribution of the data was examined through box plots (Fig. 9). The heat map of the location × treatment combinations (Fig. 10) showed the spatial patterns of stomatal conductance response under all experimental conditions. In addition, linear regression analysis (Fig. 11) confirmed the existence of a regular relationship between dust concentration and stomatal conductance. Finally, the violin–ribbon plot (Fig. 12) provided a comprehensive picture of the statistical behavior of stomatal conductance under different treatments by simultaneously displaying the complete data distribution, central indices, and confidence intervals.

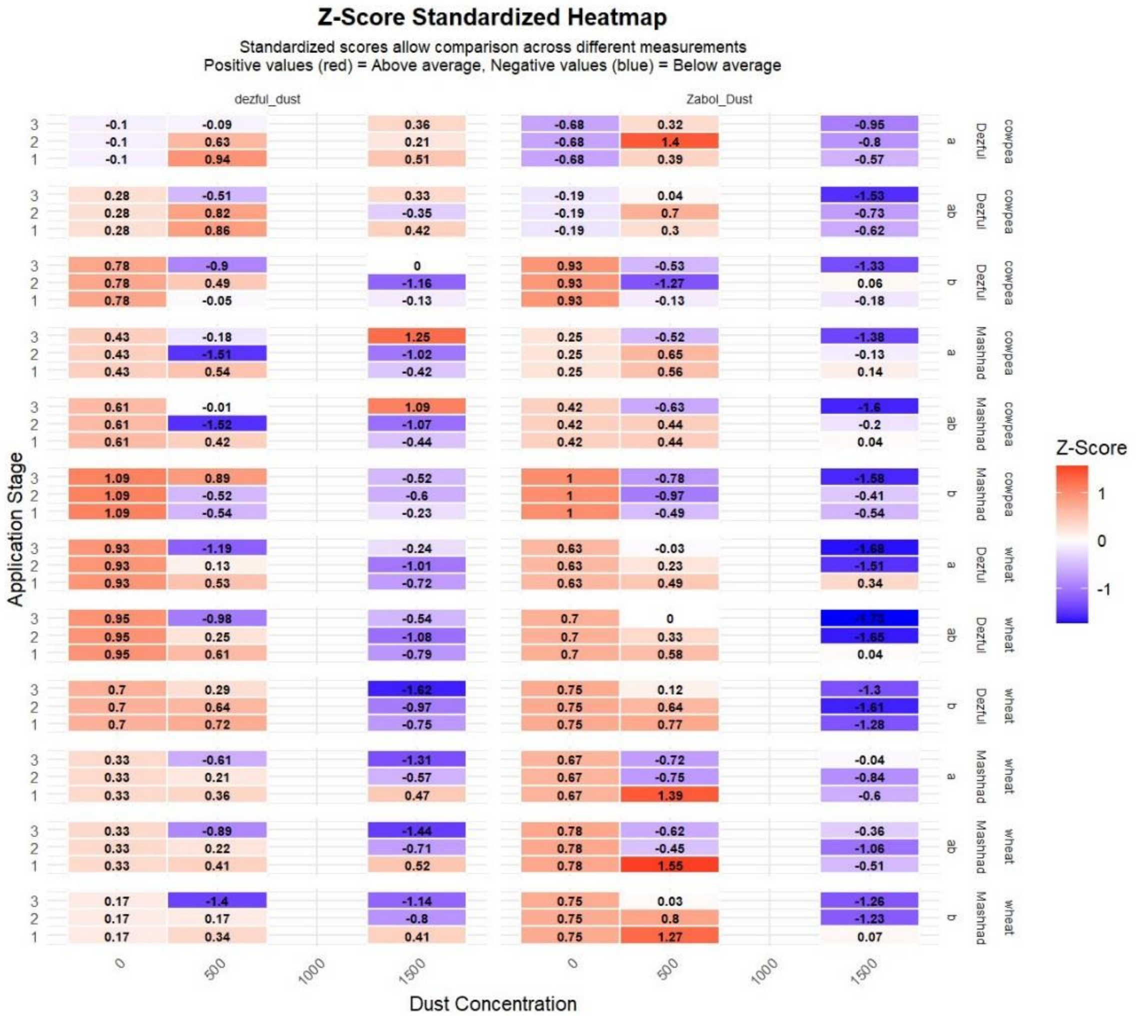

Fig. 6. Standardized Z-score heatmap of leaf chlorophyll values in both plant species and two study locations. The standardized scores allow for comparison of patterns of variation between different measurements; positive values (red) indicate values above the mean and negative values (blue) indicate values below the mean.

4. Discussion

4.1. Stomatal conductance

Exposure to dust reduces stomatal conductance in plants through two main mechanisms. First, dust particles can physically block stomata, and second, plants may actively close their stomata as a defense response to increased pollution. Consequently, a decline in stomatal conductance is expected following dust exposure. Increasing air pollution prompts stomatal closure, which progressively limits the leaf's capacity for photosynthesis and reduces overall plant assimilation (Larcher, 1995; Meravi *et al*., 2021). Similarly, Meravi *et al*. (2021) reported that dust originating from fly ash caused stomatal occlusion in several plant species, supporting the findings of the present study.

Stomatal closure is one of the earliest defense mechanisms of plants against rising air pollution. By reducing stomatal opening, gas exchange and carbon fixation are limited, leading to decreased photosynthetic activity (Seyyednejad *et al*., 2011). Zia-Khan *et al*. (2015), studying dust effects on cotton leaves, observed a 30% reduction in stomatal conductance compared with the control. They applied dust using a chamber at each treatment time and removed it afterward, reporting that dust deposition on the leaf surface induced drought-like conditions. Numerous other studies have similarly documented stomatal occlusion and reduced conductance in response to pollution (Darley, 1966; Ricks and Williams, 1974; Armbrust, 1986; Hirano *et al*., 1995; Meravi *et al*., 2021).

4.2. Chlorophyll

The reduction in chlorophyll concentration in plants exposed to dust can be attributed to the shading effect caused by the deposition of suspended particles on leaf surfaces, which also affects the chlorophyll a/b ratio (Seyyednejad *et al*., 2011; Shabnam *et al*., 2021). Chlorophyll is essential for photosynthesis, as it enables the production of carbohydrates, the primary storage and structural substance in plants. Since the mesophyll tissue in green leaves is rich in chlorophyll, leaf chlorophyll content is a reliable indicator of photosynthetic efficiency, and any reduction directly impacts plant growth (Saha and Padhy, 2011).

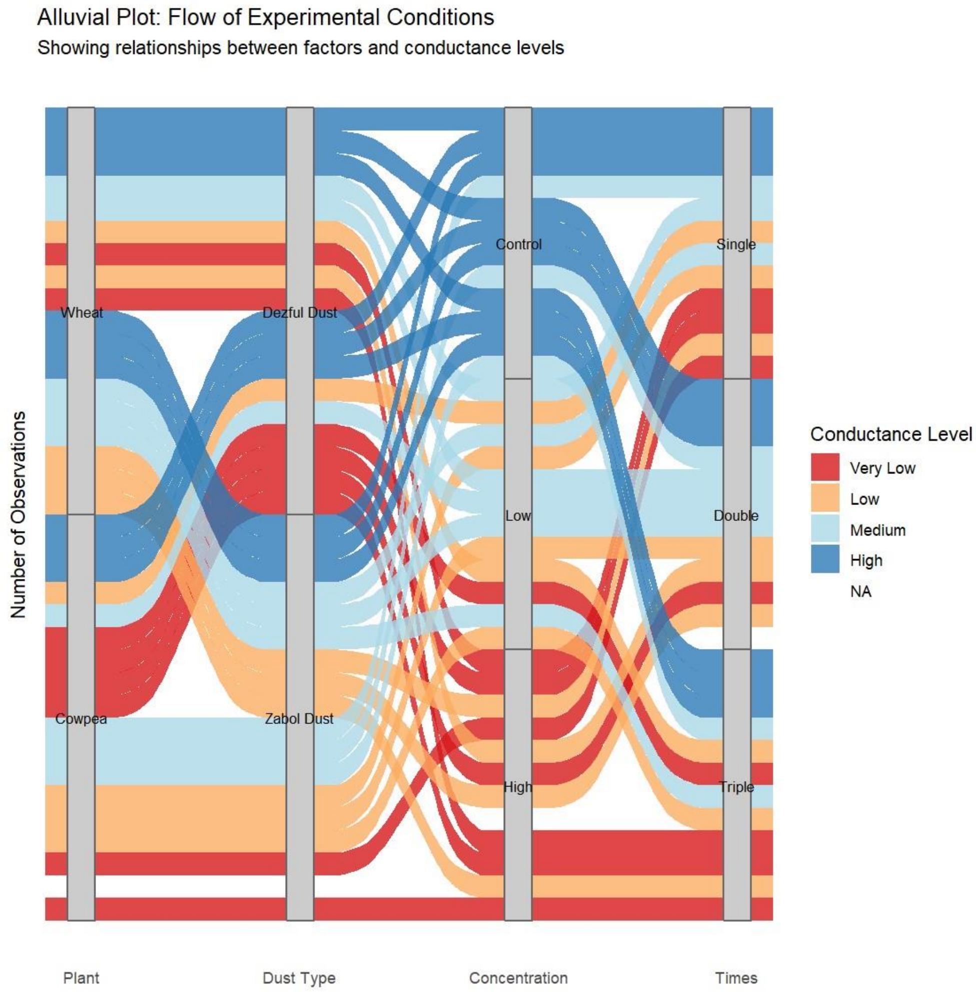

Fig. 7. Alluvial plot showing the flow of experimental conditions and the relationship between experimental factors and different levels of stomatal conductance measured in both under studied plants.

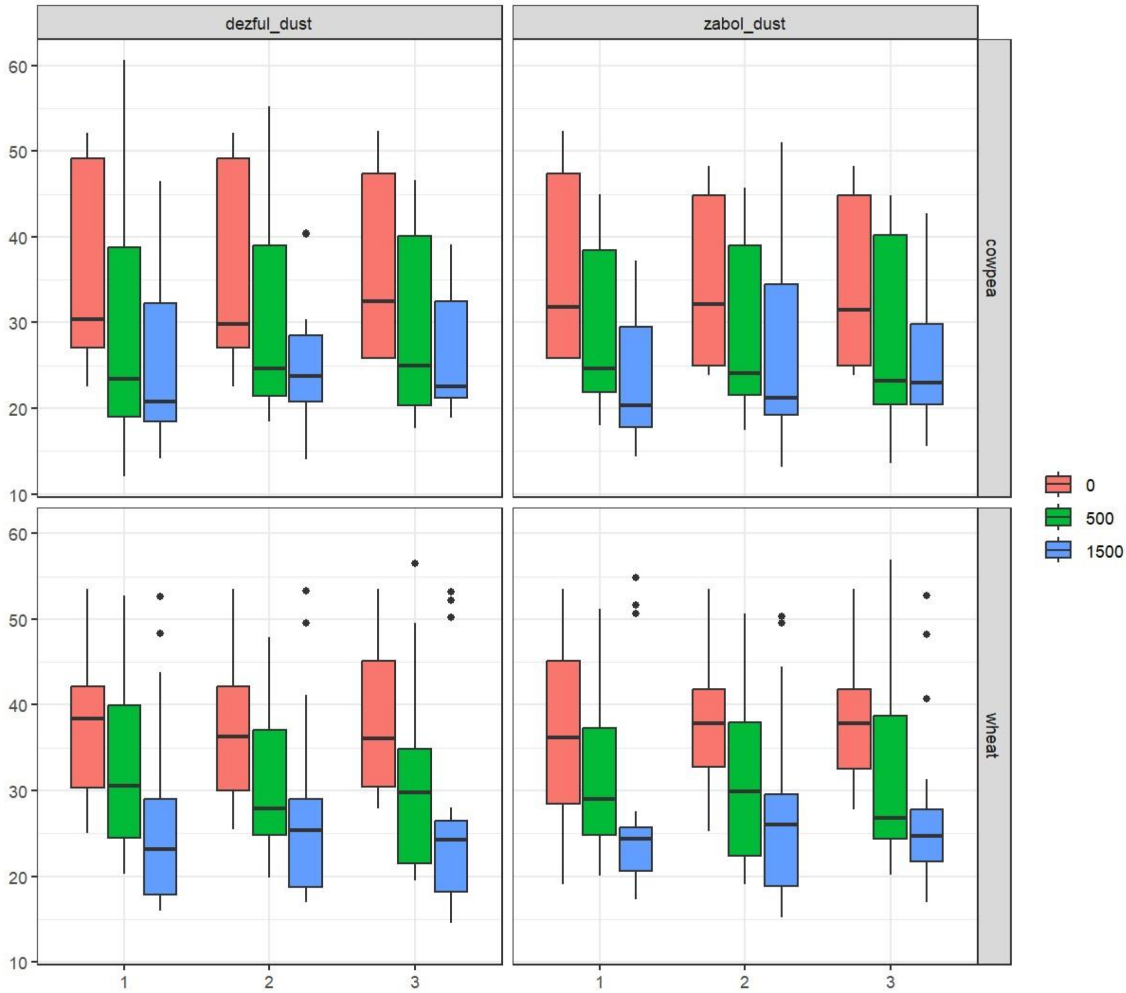

Fig. 8. Bar (or line) graph showing the mean and standard deviation of the effect of dust concentration, dust type, and dust application frequency on stomatal conductance in both studied plants.

Increasing air pollution diminishes the photosynthetic ability of leaves, leading to gradual reductions in plant growth and productivity (Larcher, 1995). For example, Darvishi Boloorani *et al*. (2020) reported a decrease in chlorophyll content in Persian Oak (Quercus brantii Lindl.) as a result of dust exposure. Similarly, Singh and Rao (1981) observed that wheat grown near a cement factory exhibited lower total chlorophyll and chlorophyll a concentrations with decreasing distance from the factory. Dust deposition on leaf surfaces likely interfered with chlorophyll synthesis by reducing light interception. Numerous other studies have also documented decreases in chlorophyll content in response to dust exposure in plants (Naidoo and Chirkoot, 2004; Prajapati and Tripathi, 2008). The differential response of wheat and cowpea to dust exposure may be attributed to their leaf morphology and surface characteristics. Narrow-leaf wheat appears more susceptible to shading and dust deposition, which reduces light interception and chlorophyll synthesis, while broad-leaf cowpea may better tolerate or compensate for dust stress, resulting in non-significant changes in chlorophyll content. Reduced stomatal conductance observed in both species likely limits CO_2 uptake, decreasing photosynthetic efficiency and potentially affecting carbohydrate production, growth, and yield. Dust deposition not only physically blocks stomata but may also induce drought-like conditions, further exacerbating reductions in gas exchange and plant productivity

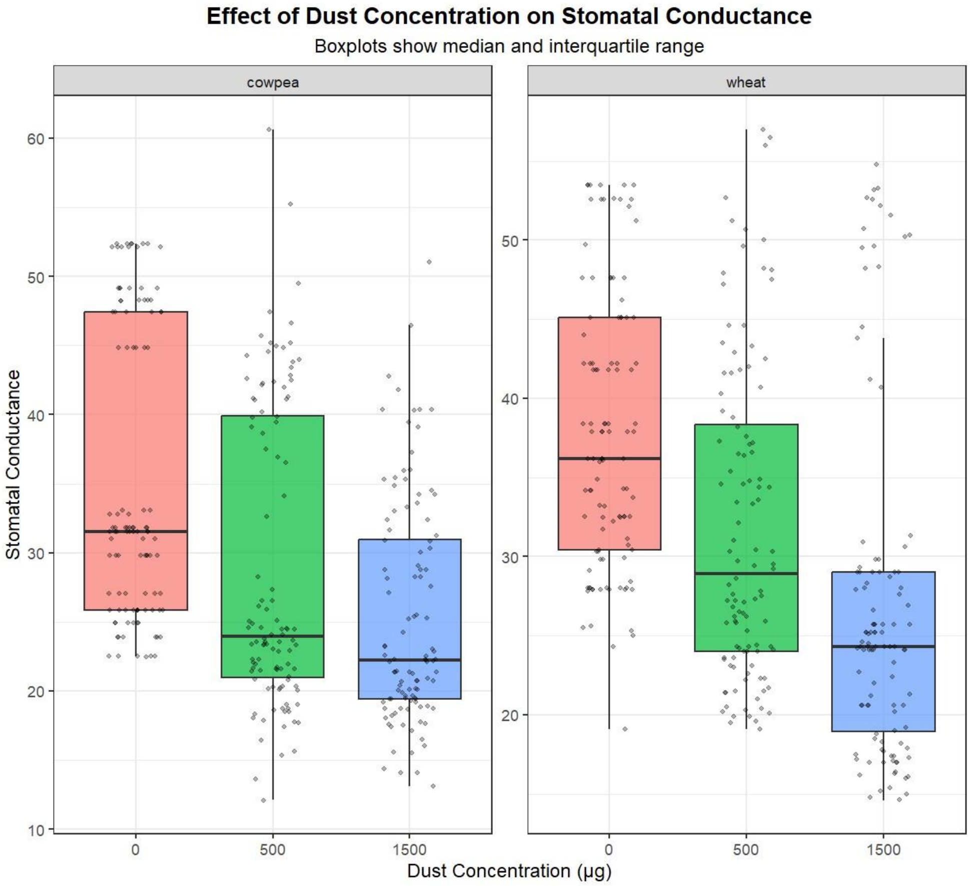

Fig. 9. Boxplot of the effect of dust concentration on stomatal conductance, showing the median and interquartile range of the data.

5. Conclusion

The results of this study demonstrate that dust application has a significant adverse effect on the stomatal conductance of both wheat and cowpea, indicating that dust deposition can impair leaf gas exchange and potentially limit photosynthetic efficiency. Chlorophyll a+b content in wheat leaves was significantly reduced under dust exposure, while cowpea leaves did not show a statistically significant change in chlorophyll content, suggesting species-specific responses to dust deposition.

Although two types of desert dust with differing chemical compositions were applied, no notable differences were observed in their effects on the measured traits. This suggests that the primary mechanisms underlying the observed responses were physical rather than chemical. Specifically, shading caused by dust deposition likely reduced light interception and chlorophyll synthesis, while stomatal occlusion directly limited gas exchange, leading to the observed declines in stomatal conductance.

These findings highlight the potential impact of dust storms on crop physiology and productivity, particularly in arid and semi-arid regions prone to frequent dust events. The differential response between narrow-leaf wheat and broad-leaf cowpea also suggests that leaf morphology may influence a plant's susceptibility to dust-related stress. This study demonstrates the importance of the effect of physical and environmental factors when assessing the effects of airborne dust on crop yield, which can be considered in agricultural management practices in dust-affected areas.

Future research should further investigate the physiological and agronomic impacts of dust deposition by directly measuring photosynthetic rate, biomass accumulation, and final yield. Detailed analysis of dust particle size, composition, and adhesion characteristics may also help clarify their specific roles in plant response. In addition, evaluating different cultivars with varying leaf morphology and tolerance levels could improve understanding of crop adaptability to dust stress and support the development of more resilient agricultural systems in dust-affected regions.

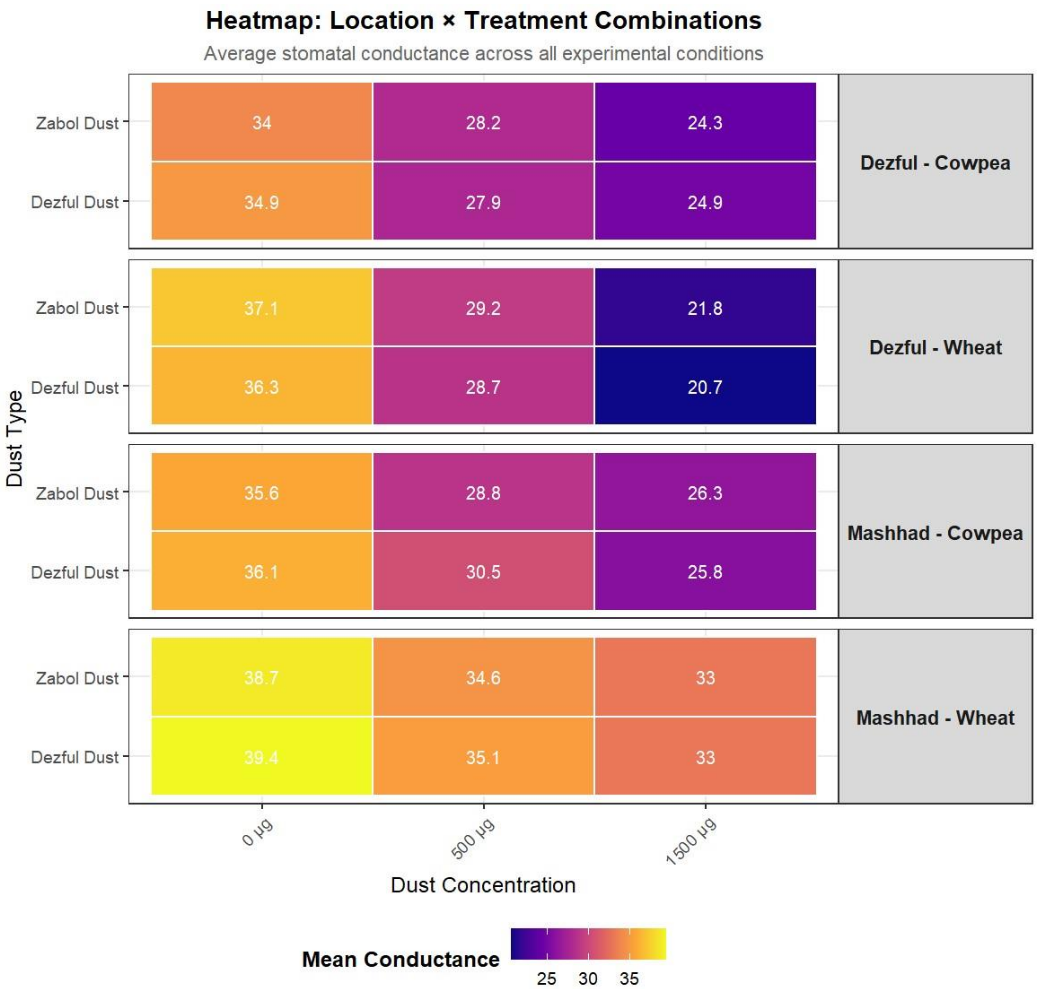

Fig. 10. Heatmap of mean stomatal conductance for different location × treatment combinations across all experimental conditions.

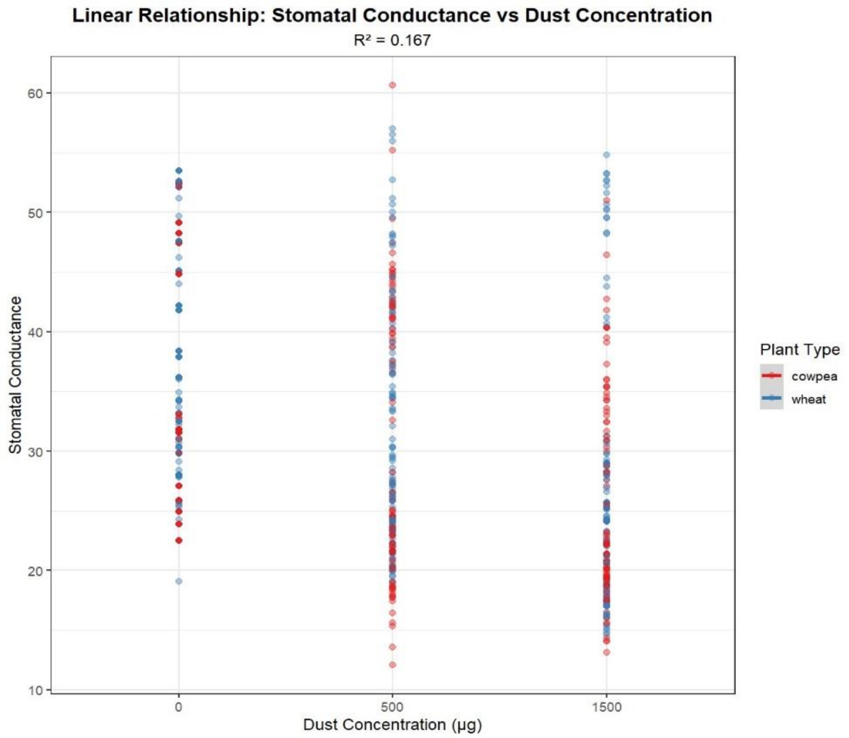

Fig. 11. Linear relationship between dust concentration and stomatal conductance of both under studied plants.

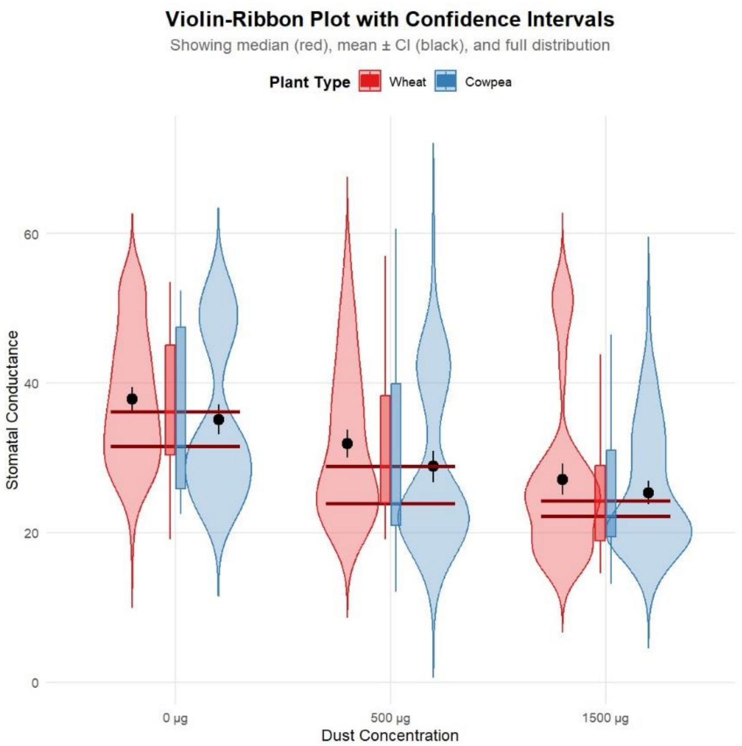

Fig. 12. Violin–Ribbon Plot showing the complete data distribution, median (red), and mean, along with confidence intervals (black) for stomatal conductance.

Author Contributions

All authors contributed to the conception and design of the study. Part of the primary data used in this study was derived from the PhD dissertation of Zahra Hatami. Z.H. collected the primary data and prepared the first draft of the manuscript. A.R. performed the computations, supervised the research process, verified the analytical methods, and prepared the maps and graphical outputs. A.R. also contributed to the literature review and data analysis. P.R. contributed to the study methodology, conceptualization, and initial execution of the research. M.N. verified the analytical methods and contributed to data analysis. All authors discussed the results, revised the manuscript critically for important intellectual content, and approved the final version of the manuscript.

Data Availability Statement

Data available on request from the authors.

Acknowledgements

Part of the primary dataset employed in this study was derived from the doctoral dissertation of Ms. Zahra Hatami at Ferdowsi University of Mashhad. The study was conducted by the same research team. The authors gratefully acknowledge Ferdowsi University of Mashhad for its institutional support.

Ethical considerations

The author avoided data fabrication and falsification.

Funding

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Conflict of interest

The authors have no conflicts of interest

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