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Effects of vehicular pollution on wheat (*Triticum aestivum* L.): physiological, morphological and yield responses across growth stages

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Abstract

Vehicular air pollution can adversely affect crop performance. This study evaluates the impact of roadside vehicular emissions on wheat (*Triticum aestivum* L.) by comparing plants grown adjacent to a busy highway (polluted site) with those at a control site ~200 m away. Growth and physiological parameters were measured at three developmental stages – crown root stage (early vegetative), anthesis (flowering), and harvest (maturity) – to capture stage-wise effects. Key traits included plant height, tiller number, flag leaf length, photosynthetic rate, chlorophyll content, and yield components (spike number, grains per spike, 1000-grain weight, and seed protein). Results showed that at the seedling stage, pollution had no significant effect on plant height or tiller count, but photosynthetic rate and chlorophyll content were already markedly reduced in highway-adjacent. plants (by 7–10% compared to controls). By anthesis, polluted plants were significantly shorter (7% height reduction, $p < 0.001$) with smaller flag leaves ($p < 0.05$), while tiller numbers remained similar. Photosynthetic rates and foliar chlorophyll at flowering were 18–30% lower under pollution stress ($p < 0.001$). By maturity, chronic pollution exposure had significantly curtailed reproductive performance: polluted plants produced ~14% fewer grains per spike and 20% lower 1000-grain weight than controls ($p < 0.001$), resulting in substantially reduced yield. Grain protein content was also ~15% lower under pollution ($p < 0.001$). These findings underscore that vehicular emissions can suppress wheat's physiological functions from early growth, culminating in stunted development and appreciable yield losses. The study highlights the need for mitigating air pollution to protect crop productivity in roadside agro-ecosystems.

Keywords: Vehicular emissions, highway, photosynthetic rate, pollution stress, agro-ecosystems

Introduction

Rapid urbanization and increasing vehicle usage have led to elevated levels of air pollution along highways and in peri-urban agricultural areas (Shrivastava *et al*. 2018) [13]. Automobiles emit a mix of noxious gases (such as carbon monoxide, nitrogen oxides (NOx), sulphur dioxide (SO_2), and ozone precursors) as well as particulate matter (including black carbon soot, dust, and lead from fuel) (Wielgosiński *et al*. 2017) [15]. Crops growing near roadsides are continuously exposed to these pollutants, which can impair plant physiology and development. Pollutant gases and fine particulates can be absorbed or deposited on leaf surfaces, causing oxidative stress and physical blockage of stomata (Muthu *et al*. 2021) [11]. Consequently, the photosynthetic machinery of plants is often compromised – for example, studies have shown that vehicular exhaust and dust lead to reduced chlorophyll a and b pigment levels in leaves. Diminished chlorophyll content directly lowers a plant's capacity for light capture and carbon fixation, ultimately affecting growth and productivity (Chaturvedi and Sharma 2024) [5]. Indeed, foliar chlorophyll and other pigment levels are widely used as bio-indicators of air pollution stress in plants.

Wheat (*Triticum aestivum* L.) is a staple cereal sensitive to air quality, and prior research indicates that chronic air pollution can significantly depress its performance (Piikki *et al*. 2008; Zhang *et al*. 2021) [12, 16]. Open-top chamber experiments and field surveys have identified ground-level ozone and NO_2 as major contributors to wheat growth and yield reductions in polluted environments. For instance, a field study in India reported that ambient pollution (near urban and industrial areas) caused significant declines in wheat plant height, biomass, and grain yield compared to cleaner rural sites (Chauhan and Joshi 2010) [6]. Reductions in net photosynthesis, leaf area, and nutrient content have been correlated with higher levels of SO_2, NOx, and particulates in the air (Mir *et al*. 2021) [10]. Over the long term, these effects on physiology translate into substantial yield losses at regional scales. It has been estimated that persistent smog and pollution have reduced wheat yields in parts of India by up to ~50% relative to their potential, accounting for most of the observed yield stagnation in recent decades (Burney and Ramanathan 2014; Gupta *et al*. 2017) [4, 8]. Such dramatic losses are attributed largely to aerosol pollutants (e.g. black carbon, fine particulates) and ozone, which together hinder crop growth far more than concurrent climate trends (Burney and Ramanathan 2014; Gupta *et al*. 2017) [4, 8].

Despite this evidence, there is a need for detailed stage-wise understanding of how pollution stress manifests over the crop life cycle. Early vegetative stages might be relatively resilient in morphology even if physiological functions are affected, whereas reproductive stages could exhibit amplified damage. This study aims to systematically evaluate the impact of vehicular pollution on wheat by comparing plants at a highway-adjacent site with those at a control site, across three key growth stages: the crown root stage (early vegetative development), anthesis (flowering), and final harvest maturity.

By measuring a comprehensive set of physiological, morphological, and yield parameters, we seek to determine at what growth stage pollution stress becomes significant and how it ultimately affects yield formation. We hypothesize that chronic exposure to vehicular emissions will lead to accumulating adverse effects, with minor differences at seedling stage that grow more pronounced by flowering and result in substantial yield penalties at maturity. Quantifying these effects not only deepens our understanding of pollution stress physiology in wheat, but also provides insight into potential yield losses for crops grown in traffic-polluted environments. The findings could inform mitigation strategies and urban planning to safeguard agricultural productivity near high-traffic areas.

Material and Method

Study Sites and Experimental Design: The study was conducted in a field environment in which two sets of wheat plots were established during the growing season. One set of plots was located adjacent to a major highway with dense traffic (the polluted site), while the other set was ~200 m away from the highway (the control site). The control distance was chosen to represent substantially lower exposure to vehicular emissions (as pollutant concentrations drop off with distance from the road). Both sites had similar soil type, irrigation, and management practices to ensure that observed differences could be attributed chiefly to air quality differences. The wheat variety grown was a locally cultivated *T. aestivum* cultivar, sown at the same time in both sites. Standard agronomic practices (seed rate, fertilizer application, and pest management) were uniformly applied.

Growth Stages and Sampling: To capture the temporal progression of pollution effects, measurements were taken at three developmental stages of the wheat crop- Crown Root Stage (early vegetative stage), approximately 3–4 weeks after germination, when seedlings had established initial tillers and crown roots. At this stage, nine representative plants per site were sampled for measurement. Anthesis Stage (flowering stage), when plants had fully developed stems, and flowering had commenced (around 90 days after sowing). Nine randomly selected plants per site (ensuring they were healthy and representative of average stand conditions) were measured at anthesis. Harvest Maturity, at physiological maturity (~120 days after sowing), when grain filling was complete. At harvest, measurements were taken on a sample of plants (n = 9 per site) to assess final yield components.

Measured Parameters- At each stage, we evaluated a suite of morphological and physiological parameters:

Plant height was measured from the soil surface to the tip of the tallest leaf (at crown stage and anthesis) or to the tip of the spike/excluding awns (at maturity), for each sampled plant. Height reflects overall vegetative growth and biomass accumulation. Tiller number per plant were count. At crown stage and anthesis, total tiller number was recorded. At harvest, we distinguished total tillers vs. effective tillers, where “effective tillers” refers to those that bore a productive spike (these are equivalent to number of spikes per plant). At anthesis and harvest, the length of the flag leaf (the uppermost leaf on the stem) was measured, as an indicator of leaf area and photosynthetic tissue available during grain filling. The net photosynthesis of fully expanded leaf at crown stage and flag leaves at latter stages were measured.

Leaf chlorophyll was assessed by collecting fresh leaf samples and extracting chlorophyll in an 80% acetone solution. The absorbance was measured with a spectrophotometer and chlorophyll $a + b$ content was calculated (using standard formulas) and expressed as mg per g fresh weight (mg g^{-1} fw). This parameter indicates the pigment concentration in leaves. At least three composite leaf samples per site per stage were analysed. After physiological maturity, the following yield components were measured on each sampled plant- Number of spikes per plant (effective tillers as defined above). Spike length, the length of each spike (cm) from base to tip (excluding awns), averaged per plant. Grains per spike, the number of fully developed grains counted on the main spike of each plant (and additional spikes averaged, if multiple spikes per plant). 1000-grain weight, a standard measure of grain size, calculated by weighing a random sample of grains and scaling to 1000 grains (in grams). Here we determined the average weight of grains from each plant’s spikes and extrapolated to 1000-grain weight. Total seed protein content, grains from each plant were oven-dried and ground to analyse seed protein concentration. Crude protein (% of grain dry weight) was determined using the Kjeldahl method (nitrogen content × 6.25) and is reported in mg protein per g grain. This reflects grain nutritional quality.

Statistical Analysis: Data from the polluted and control sites were compared to identify significant differences attributable to pollution exposure. For each growth stage and parameter, a two-sample comparison (independent *t*-test) was performed between the control and highway-exposed groups. Prior to analysis, data were checked for normality and homogeneity of variances; transformations were applied if needed to meet test assumptions. Significance was evaluated at the $\alpha = 0.05$ level, with $p < 0.05$ considered statistically significant. More stringent thresholds ($p < 0.01$, $p < 0.001$) are reported where applicable to denote highly significant differences. Summary statistics (mean ± standard deviation) for each parameter at each site were computed. All analyses were conducted using standard statistical software. The results are presented as mean values with indications of significance, and percent differences are given to illustrate the magnitude of pollution impact.

Results

Crown Root Stage (Early Vegetative Stage)

At the crown root stage, wheat plants at the polluted (highway-edge) site did not show notable visible stunting compared to control plants in terms of gross morphology like height or tiller count. Plant height averaged 21.9 cm (±2.0) for control seedlings versus 21.0 cm (±1.5) for polluted-site seedlings, a difference that was not statistically significant ($p > 0.1$). Similarly, the number of tillers per plant was virtually identical between the two groups at this early stage (averaging about 2–3 small tillers each, with no significant difference). These results suggest that initial establishment and structural growth of young wheat were not markedly hindered by proximity to vehicular pollution.

In contrast, even at this early developmental stage, significant differences were detected in physiological parameters. The net photosynthetic rate of leaves was substantially lower in seedlings growing by the highway. Control seedlings exhibited a photosynthetic rate of about 11.0 ± 0.8 μmol CO_2 m^{-2} s^{-1}, whereas polluted-site seedlings averaged only around 10.1 ± 0.8 μmol CO_2 m^{-2} s^{-1} – approximately a 8.2% reduction under polluted conditions. This indicates that the roadside plants were assimilating carbon at a lower rate than their counterparts in cleaner air. Consistently, foliar chlorophyll content was also depressed at the polluted site. Total chlorophyll (a + b) in control seedlings was about 8.3 mg g⁻¹ (fresh weight basis), compared to only ~7.5 mg g⁻¹ in the highway-exposed seedlings, reflecting roughly a 9.6% decrease in chlorophyll levels due to pollution. The difference in leaf greenness was visibly apparent, with control leaves having a richer green hue while some polluted-site leaves appeared slightly chlorotic. The fact that photosynthesis and chlorophyll – two closely linked indicators of plant physiological health – were significantly lower in the absence of any height or biomass differences suggests that vehicular emissions imposed a physiological stress on wheat from the earliest growth stages, even though structural growth (height/tillers) had not yet diverged.

Anthesis (Flowering Stage)

By the time of anthesis, clearer impacts of the polluted environment on plant growth became evident. Plant height at flowering was significantly reduced in wheat plants near the highway. Control plants reached an average height of approximately 89.6 cm (tall, healthy canopies nearing a meter), whereas polluted-site plants averaged around 83.4 cm in height – making them about 6–7% shorter on average ($p < 0.001$ for the height difference). This indicates a statistically significant stunting of plant stature under chronic exposure to vehicular exhaust. Field observations confirmed that the polluted wheat plots had a somewhat shorter canopy and smaller overall biomass by anthesis, compared to the lush growth at the control site.

Leaf morphology was also affected. The length of the flag leaf (the uppermost leaf below the spike) was significantly smaller in polluted plants. Control plants' flag leaves averaged ~13.0 cm in length, whereas those at the polluted site averaged only ~11.6 cm, roughly 10–12% shorter ($p \approx 0.014$). Shorter flag leaves imply reduced photosynthetic area available during the critical flowering and grain-filling period. Despite these differences in height and leaf size, the number of tillers per plant at anthesis remained comparable between the two treatments. Control plants had on average 9.7 tillers, versus 9.4 in polluted plants, and this slight difference was not statistically significant. Thus, even under pollution stress, the wheat plants managed to initiate a similar number of shoots, suggesting that tiller initiation was not the primary trait affected by pollution up to mid-season.

Physiological measurements at anthesis reinforced the trends noted earlier at the seedling stage, with even larger gaps between control and polluted plants. The photosynthetic rate of flag leaves in control plants was about 11.9 μmol CO_2 m^{-2} s^{-1} (at midday), whereas polluted plants showed a significantly lower rate of ~9.8 μmol CO_2 m^{-2} s^{-1} – an around 18% reduction in photosynthetic capacity due to the polluted atmosphere ($p < 0.001$). Similarly, chlorophyll content in flag leaves at flowering was drastically lower under pollution. Control plants had around 9.17 mg g⁻¹ FW of chlorophyll, compared to only about 6.43 mg g⁻¹ FW in polluted plants, amounting to roughly a 30% loss of chlorophyll ($p < 0.001$). These differences were highly significant and would be expected to impair the energy capture and carbon assimilation during a phase when the plant's energy demands (for reproduction) are peaking.

Harvest Stage (Maturity and Yield)

By harvest time, the cumulative effects of growing under polluted vs. clean air conditions were starkly reflected in both the final growth metrics and the yield outcomes of the wheat crop. Final plant height at maturity averaged 92.6 cm for control plants, compared to 85.0 cm for plants at the highway site – an 8% reduction in height under pollution ($p < 0.001$). Thus, the gap in height observed at anthesis not only persisted but slightly widened by harvest. Control wheat had robust, tall stalks, whereas polluted wheat stalks were consistently shorter, confirming that pollution-related growth suppression carried through to the end of the lifecycle.

The flag leaf length at maturity remained significantly smaller in polluted plants (on average 12.7 cm) relative to controls (14.5 cm; $p < 0.01$). This mirrors the anthesis observation, indicating that the leaf area contributing to late-season photosynthesis (critical for grain filling) was reduced under pollution. In terms of tillering, the total number of tillers per plant at maturity was still not significantly different between treatments: control plants had ~9.7 tillers vs. ~9.4 tillers for polluted plants (virtually the same as at anthesis, with $p > 0.2$, n.s.). This suggests that the initial formation of tillers was unaffected by pollution in terms of quantity. However, a subtle difference emerged in productive tillers (effective tillers or spikes per plant). Control plants averaged about 7.56 spikes per plant, whereas polluted plants averaged 6.89 spikes. This represents roughly a 9% decrease in the number of spikes (grain-bearing heads) per plant under polluted conditions. Statistically, this difference was not very strong ($p < 0.19$, not significant at 0.05 level), indicating high variability; nonetheless, the trend implies slightly fewer tillers of the polluted plants actually survived or developed into fertile spikes by harvest. Thus, while similar numbers of tillers were initiated, a few more tillers may have aborted or remained non-productive under pollution stress.

Importantly, multiple yield components were significantly impaired in the pollution-exposed wheat, translating into lower overall grain yield and quality. Spike length, the ears (spikes) of wheat from the polluted site were markedly shorter. Control spikes averaged ~11.3 cm long, whereas polluted spikes averaged only ~9.4 cm, roughly 17% shorter on average ($p < 0.001$). Shorter spikes often have fewer florets, which can lead to fewer grains set. Grains per spike, control plants produced an average of about 40.1 grains per spike, while polluted plants produced only about 34.7 grains per spike. This is an approximate 14% reduction in the number of grains formed on each spike under polluted conditions ($p < 0.001$). In practical terms, many spikes on polluted plants were visibly less filled, with some spikelets containing underdeveloped or missing grains, whereas control spikes were generally well-grained from base to tip. 1000-grain weight, the size and weight of individual grains were also significantly affected. The mass of 1000 grains (a standard indicator of grain size/plumpness) from control plots was about 44.9 g, compared to only 36.1 g for the polluted plot grains – approximately 20% lower grain weight in the polluted wheat ($p < 0.001$). This sizable reduction indicates that grains from plants breathing vehicular exhaust were smaller and lighter, likely due to limited photosynthate supply and/or stress during grain filling. Total seed protein, grain quality in terms of protein content was diminished by pollution exposure. Control wheat grains had an average protein concentration of ~12.3 mg g⁻¹, whereas polluted wheat grains had about ~10.5 mg g⁻¹, which is ~15% lower protein content ($p < 0.001$). Although both sets of grains fall within typical ranges for wheat, the polluted grains' protein drop is significant, potentially affecting their nutritional and baking quality. This could result from altered nitrogen assimilation or stress-induced changes in grain composition under polluted conditions.

In addition to these yield and quality metrics, physiological differences between the two sets of plants remained extreme at the end of the season. The photosynthetic rate during the grain-filling period (late season measurement on flag leaves) in control plants was ~10.0 µmol CO_2 m^{-2} s^{-1}, whereas polluted plants showed a drastically lower rate of ~5.5 µmol CO_2 m^{-2} s^{-1}. This is roughly a 45% reduction in photosynthetic rate at maturity ($p < 0.001$). Essentially, the polluted wheat's photosynthesis had nearly halved compared to normal by the time of grain filling, which is consistent with severe stress. Correspondingly, chlorophyll content in flag leaves at harvest was also much lower in polluted plants (averaging ~4.64 mg g^{-1}) relative to controls (~7.33 mg g^{-1}), a 37% decline ($p < 0.001$). Many flag leaves in the polluted plots had turned yellow or senesced faster, reflecting chlorophyll loss, whereas control plot flag leaves stayed green longer into the grain-filling stage. These physiological deficits align with the observed yield reductions: with significantly less chlorophyll and photosynthetic activity in late season, polluted plants would have generated and transported fewer assimilates to the developing grains, resulting in fewer and lighter grains.

Table 1: Growth parameters (Crown root, anthesis and physical maturity stage) and yield parameters (Physical maturity stage) of wheat plants grown at Control Sites (200 m away from highway) and adjacent to highway

Growth stage	Parameters	Wheat Control Site	Wheat Experimental Site
Crown stage	Height (cm)	21.9 ± 1.5	21.0 ± 0.8
	Number of tillers	3.0 ± 0.5	3.0 ± 0.5
	Photosynthetic rate (µmol CO_2 m^{-2} s^{-1})	11.0 ± 0.8	10.1 ± 0.8
	Chlorophyll content (mgg^{-1} fw)	8.3 ± 1.0	7.5 ± 0.7
Anthesis stage	Height (cm)	89.7 ± 2.9	83.4 ± 2.0
	Leaf Size (Flag leaf length in cm)	13.0 ± 1.1	11.6 ± 1.0
	Number of tillers	9.7 ± 0.7	9.4 ± 0.9
	Photosynthetic rate (µmol CO_2 m^{-2} s^{-1})	11.9 ± 0.8	9.8 ± 1.1
	Chlorophyll content (mgg^{-1} fw)	9.2 ± 1.0	6.4 ± 1.0
Harvesting stage	Height (cm)	92.6 ± 3.4	85.0 ± 3.5
	Leaf Size (Flag leaf length in cm)	14.5 ± 1.2	12.7 ± 1.1
	Number of tillers	9.7 ± 1.4	9.4 ± 0.7
	Effective tillers	7.6 ± 1.1	6.9 ± 0.9
	Number of spikes per plant	7.6 ± 1.1	6.9 ± 0.9
	Spike length (cm)	11.3 ± 0.6	9.4 ± 0.5
	Number of grains per spikes	40.1 ± 0.9	34.7 ± 1.4
	1000 grains weight (g)	44.9 ± 1.7	36.1 ± 2.0
	Photosynthetic rate (µmol CO_2 m^{-2} s^{-1})	10.0 ± 0.9	5.5 ± 0.7
	Chlorophyll content (mgg^{-1} fw)	7.3 ± 1.1	4.6 ± 1.1
	Total seed protein content (mgg-1)	12.3 ± 0.5	10.5 ± 0.3

Discussion

The findings of this study clearly demonstrate that chronic vehicular pollution imposes stress on wheat crops, progressively impairing physiological function and ultimately reducing growth and yield. The stage-wise assessment revealed an important pattern- physiological stress signals (reduced photosynthesis and chlorophyll) appeared early, even when morphological growth was still unaffected, whereas significant morphological and yield impacts manifested later in development as the stress accumulated.

At the crown root (seedling) stage, wheat in the polluted environment maintained normal height and tiller number, indicating that early vegetative growth was initially resilient in terms of structure. However, the slightly depression in photosynthetic rate and chlorophyll content in polluted seedlings suggests initiation of damage or inhibition was underway. These early physiological perturbations likely stem from exposure to traffic-related pollutants such as NO_2, SO_2, and particulate matter. Such pollutants can cause stomatal closure or block stomatal openings with deposited particulates, reducing CO_2 uptake (Muthu *et al*. 2021) [11]. They can also generate reactive oxygen species that damage chloroplasts and degrade chlorophyll molecules (Lemke and Woodson 2024) [9]. In line with our observations, controlled experiments have shown that even short-term exposure to common vehicular pollutants can reduce chlorophyll biosynthesis and photosynthetic efficiency in plants (Chauhan and Joshi 2010; Abo-Hamad 2019) [1, 6]. Therefore, the roughly one-third reduction in seedling photosynthesis and chlorophyll at the highway site is a strong indicator that the young plants were experiencing stress at the biochemical level (likely from oxidative damage or inhibited pigment production), even though they hadn't yet visually stunted.

By the time of anthesis (flowering), the cumulative impact of pollution became evident in the plant morphology. Polluted wheat was significantly shorter and had smaller flag leaves than control wheat. This stunting effect corroborates numerous field studies that document growth suppression in crops chronically exposed to urban or roadside air pollution. In a study, Chauhan and Joshi (2010) [6]. noted significant reductions in wheat plant height when grown near industrial areas with high SO_2 and NOx levels, relative to cleaner sites. Our results align with those findings of Abo-Hamad (2019), Singh *et al*. (2023) [14]. The fact that tiller numbers remained equal suggests that pollution did not prevent the initiation of shoots, but rather constrained the subsequent expansion and elongation of those shoots (perhaps due to limited photosynthetic outputs). In essence, the plants tried to maintain the same "branching" strategy (tillering) but each tiller grew less in polluted air.

The persistent decline in photosynthetic rate and chlorophyll content in polluted plants at anthesis (20–30% lower than controls) indicates a sustained physiological handicap. This continued depression is consistent with the notion of chronic stress: the plants near the highway never attained the photosynthetic capacity of the control plants at any point, likely due to ongoing pollutant injury. Literature reports similar magnitudes of reduction in photosynthetic capacity and chlorophyll content (Abo-Hamad 2019; Anjum *et al*. 2021; Singh *et al*. 2023) [1, 3, 14].

Mechanistically, prolonged pollutant exposure leads to chlorophyll loss and impaired gas exchange, either through direct toxic effects of gases like ozone (which oxidize cellular membranes and chlorophyll) or accumulation of particulates on leaf surfaces that attenuate light and clog stomata (Anjum *et al*. 2021). Our anthesis data fits this paradigm: polluted wheat had the hallmark signs of pollution injury – chlorotic leaves and lower photosynthesis – which would inevitably translate to reduced growth. Notably, the anthesis stage is when the plant's source capacity (photosynthetic machinery) and sink formation (developing grains) are both highly active, so any deficit in assimilation at this stage can directly constrain yield potential.

By the harvest stage, the consequences of season-long pollution exposure on reproductive performance were striking. Polluted plants, despite having a similar count of tillers, yielded fewer spikes per plant (a slight reduction) and those spikes were significantly smaller and less fertile (fewer grains). Additionally, grains from polluted plants were lighter and poorer in protein. These findings are strongly supported by previous research on pollution and crop yields. For example, in a study near roadways, (Abo-Hamad 2019). found that wheat plants just 1 meter away from a busy road had 40–60% fewer grains per spike and ~19% lower 1000-grain weight compared to plants merely 100 cm further from the road. Our observed ~14% reduction in grains per spike and ~20% reduction in grain weight for highway-proximate plants relative to 200 m away are in line with those distance-gradient experiments, albeit less extreme (since our "control" was a few hundred meters away, not just 1 m). The consistency of these results underlines that vehicular pollution – likely through a combination of ozone damage, nitrogen dioxide toxicity, and deposition of soot and heavy metals – directly impairs the reproductive success of wheat (Geddes and Murphy 2012; Anand *et al*. 2022) [2, 7]. Pollutants can cause flower and seed abortion, reducing grains per spike, and limit carbohydrate availability during grain filling, resulting in shriveled, lightweight grains. Moreover, heavy metals like lead (from leaded gasoline or tire wear) can accumulate in roadside soils and plants, interfering with enzymes involved in grain development and protein synthesis. The slightly lower number of effective spikes in polluted plants suggests some tillers failed to set seed, possibly due to stress-induced abortion of weaker tillers or spikes.

Conclusion

This research provides a comprehensive, stage-by-stage analysis of how chronic vehicular pollution impacts wheat growth and productivity. Wheat plants grown adjacent to a busy highway experienced early physiological stress (lower photosynthesis and chlorophyll) that translated into noticeable growth suppression by flowering and severe yield losses by harvest. Key yield attributes – including grains per spike, grain weight, and seed protein content – were significantly reduced in plants exposed to traffic emissions, resulting in an overall decline in yield and quality relative to plants in cleaner air. These findings demonstrate that even in the absence of obvious injury symptoms, air pollution from vehicles can quietly stunt crop performance and curtail agricultural output.

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