International Journal of Advanced Research in Engineering Technology & Science ISSN: 2349-2819

Email: editor@ijarets.org Volume-6, Issue-12 December- 2019 www.ijarets.org

Accumulation and Toxicological Effects of Cadmium and Lead from Vehicular Pollution on Wheat Plants

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Abstract

A major source of heavy metal pollution, especially lead (Pb) and cadmium (Cd), which are extremely dangerous to agricultural ecosystems, is vehicular emissions. The build-up of these harmful elements is particularly dangerous for wheat (Triticum aestivum L.), a staple crop grown all over the world. The build-up of Cd and Pb from vehicle pollution and its toxicological consequences on wheat plants are examined in this study. Comprehensive reviews of the body of existing research are integrated with experimental data in this work. Results show that exposure to these metals negatively affects photosynthesis, growth, and yield, among other physiological and biochemical processes in wheat. The use of chelating agents and phytoremediation are two mitigation techniques that are considered to solve these issues.

Introduction

In the Delhi NCR region, where substantial agricultural activity coexists with fast urbanization and industrial expansion, vehicular pollution has become a concerning problem. The area is particularly vulnerable to the negative impacts of vehicle emissions because of this peculiar fusion of urban and rural dynamics. Harmful pollutants, including heavy metals like lead (Pb) and cadmium (Cd), are being released at an exponential rate in Delhi NCR due to the unrelenting growth in the number of automobiles. These metals are sneaky pollutants that linger in the environment, especially in soil and vegetation, and are results of burning fossil fuels. This pollution, which has significant effects on both the environment and people, is carried by Delhi NCR's extensive highways and arterial roadways.

One major environmental issue in Delhi NCR is the deposition of heavy metals like Cd and Pb on agricultural fields near roadways. Runoff from surrounding roadways and air debris deposit these metals on the soil and plant surfaces. Because of their non-biodegradable and bioaccumulative characteristics, Cd and Pb are hazardous and provide a continuous danger to ecosystems. Wheat, a main crop in India, is especially susceptible to this kind of contamination in the agricultural setting. Since it is a crop of great economic and nutritional significance, any reduction in its quality and production brought on by heavy metal contamination presents two risks: financial losses for producers and health hazards for consumers. This issue is particularly acute in Delhi NCR, where wheat farms are frequently located near

Cd and Pb, despite being non-essential elements for plant growth, exhibit significant toxic effects on plant physiology and biochemistry. These metals interfere with nutrient uptake, disturb enzyme activity, and generate oxidative stress, which collectively impair plant growth and productivity. Wheat plants grown near high-traffic highways in Delhi NCR often show signs of reduced growth, such as stunted plant height, smaller leaf area, and diminished biomass. The absorption and translocation of these metals within plant tissues further exacerbate their toxic effects. Cd and Pb predominantly accumulate in the roots, but their translocation to shoots and grains poses a direct risk to the food chain. For the residents of Delhi NCR, where wheat forms a substantial part of the diet, this contamination translates into potential health hazards, including kidney damage, neurological issues, and developmental delays.

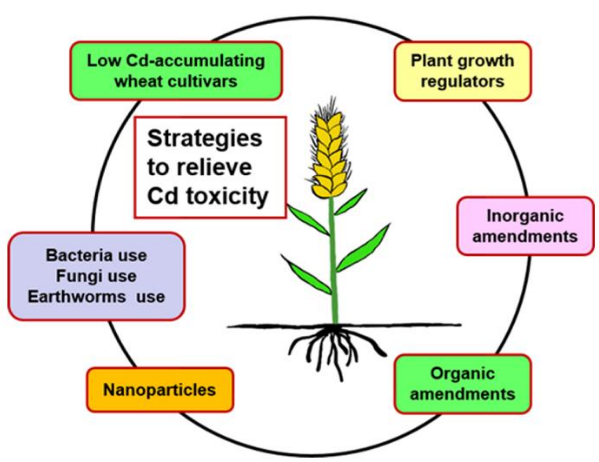

Fig: Steategies to relieve cd toxicity.

Cd and Pb have a significant and complex metabolic effect on wheat plants. Photosynthesis impairment is one of the first signs of heavy metal poisoning. The oxidative stress brought on by these metals causes chlorophyll to degrade, which significantly reduces photosynthetic efficiency. This results in decreased plant vigour and yields for the wheat harvests grown in Delhi NCR. Additionally, reactive oxygen species (ROS) are produced in plant cells in response to the presence of Cd and Pb. Antioxidant enzymes like catalase and superoxide dismutase (SOD) provide plants with a defensive mechanism, but continuous exposure to heavy metals overwhelm these defenses, resulting in oxidative damage.

The dose-dependent toxicological effects of Cd and Pb on wheat plants are demonstrated by controlled pot experiments carried out in Delhi NCR to mimic field settings. The detrimental impacts on plant development metrics, including plant height, leaf area, and biomass, intensify as the concentrations of these metals in the soil rise. For example, compared to control plants grown in uncontaminated soil, wheat plants exposed to greater amounts of Cd and Pb show noticeably slowed development and lower biomass. These results highlight the pressing need for measures to lessen the negative effects of heavy metal pollution on Delhi NCR's agricultural sector.

Vehicle pollution has effects on agricultural productivity and quality in addition to the physiological and biochemical well-being of plants. The grain yield of wheat cultivated in Delhi NCR's polluted soils is much lower. The combined impacts of reduced photosynthesis, oxidative stress, and nutritional imbalances brought on by heavy metal poisoning directly result in this yield reduction. Food safety is seriously threatened by the often-measurable amounts of Cd and Pb in the grains that are harvested from these crops. This contamination has serious repercussions for public health and food security in an area like Delhi NCR, where a sizable section of the populace depends on locally farmed vegetables.

The necessity for strict monitoring and regulation of vehicle emissions in Delhi NCR is further highlighted by the presence of Cd and Pb in wheat grains. Although a number of programs and regulations have been put in place to reduce air pollution in the area, it is still unclear how effective they are in lowering the levels of heavy metal contamination in agricultural areas. The results of this study highlight the need for an integrated strategy that incorporates agricultural management techniques with pollution control strategies. One promising method for immobilizing heavy metals in the soil and lowering their availability for plant uptake is the use of soil amendments like organic matter and biochar.

It is impossible to ignore the socioeconomic effects of heavy metal poisoning in Delhi NCR's wheat harvests. The region's farmers frequently deal with diminishing agricultural yields and quality, which lowers their revenue and undermines their economic stability. This problem is especially disastrous for small-scale farmers who depend on agriculture as their main source of income. Furthermore, the health hazards of eating tainted wheat directly affect the healthcare system as rising rates of heavy metal poisoning put a pressure on infrastructure and medical resources. Coordination between many stakeholders, including governmental organizations, academics, and local communities, is necessary to address these issues.

In order to address vehicle pollution and its effects on agriculture, public education and awareness campaigns are essential. The effects of heavy metal pollution in food crops and the steps residents of Delhi NCR may take to reduce their exposure should be explained to them. Some actions that can greatly reduce vehicle pollution in the area include enforcing tougher emission regulations, encouraging the use of public transportation, and encouraging the adoption of cleaner fuels. Furthermore, encouraging cooperation between environmental and agricultural experts might open the door to creative ways to deal with this urgent problem.

In the study of Cd and Pb accumulation in wheat plants near high-traffic highways in Delhi NCR highlights the urgent need for interventions to mitigate the impact of vehicular pollution on agriculture. The findings reveal the toxicological effects of these heavy metals on plant growth, development, and productivity, as well as the potential health risks posed to consumers. For a region as dynamic and densely populated as Delhi NCR, addressing the challenges of heavy metal contamination requires a holistic approach that integrates pollution control, agricultural management, and public awareness. By prioritizing sustainable practices and fostering a culture of environmental responsibility, Delhi NCR can pave the way for a healthier and more resilient future for its residents and agricultural systems.

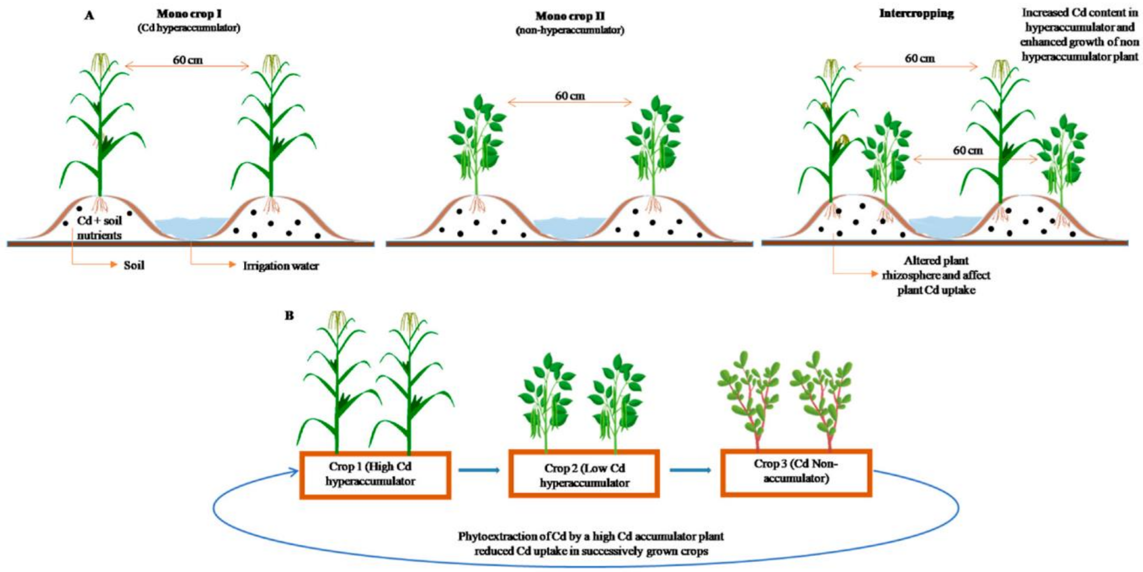

Fig: Agricultural Strategies to Reduce Cadmium Accumulation.

Aims and Objectives

- To quantify the levels of Cd and Pb in soil and wheat plants near high-traffic zones.
- To evaluate the physiological and biochemical impacts of Cd and Pb on wheat growth and yield.
- To assess the mechanisms of Cd and Pb uptake, translocation, and accumulation in wheat plants.
- To propose mitigation strategies to minimize the toxic effects of Cd and Pb on wheat cultivation.

Review of Literature

The accumulation of heavy metals in plants has been extensively studied, with particular emphasis on Cd and Pb due to their high toxicity and persistence in the environment. Studies indicate that vehicular emissions are a primary source of Cd and Pb contamination in soils near highways and urban areas. Cd and Pb uptake by plants occurs predominantly through roots, but foliar absorption also contributes significantly, especially in areas with high atmospheric deposition. The toxic effects of these metals include oxidative stress, disruption of nutrient balance, and inhibition of photosynthetic activity. Moreover, Cd and Pb have been shown to interfere with essential enzymatic activities, leading to reduced growth and productivity in crops.

The accumulation of heavy metals, particularly cadmium (Cd) and lead (Pb), in plants has long been a subject of profound scientific inquiry due to their high toxicity, persistence in the environment, and detrimental impacts on both plant and human health. The issue is not merely an environmental concern; it is also a deeply human one, touching lives through its effects on food security, agriculture, and overall ecosystem stability. As the world continues to urbanize and industrialize, understanding the dynamics of heavy metal accumulation in plants has become more crucial than ever.

Vehicular emissions stand out as a significant contributor to the contamination of soils by Cd and Pb, especially in regions near highways and urban centers. The dense network of roads, bustling with vehicles expelling exhaust gases laden with heavy metal particles, forms a constant source of contamination. This insidious process gradually infiltrates the soil, with these metals binding tightly to soil particles. The proximity of agricultural lands to such contamination sources amplifies the risks, as crops grown in these areas inadvertently absorb these toxic elements. The human aspect of this issue is stark: the crops that feed communities and sustain livelihoods become tainted, posing long-term health risks to those who consume them.

The uptake of Cd and Pb by plants predominantly occurs through their root systems, which act as natural filters and absorbers for water and nutrients from the soil. However, in regions with elevated levels of atmospheric deposition, foliar absorption becomes a significant pathway for these metals to enter plants. This dual mode of entry highlights the pervasive nature of heavy metal contamination, demonstrating how no part of a plant is spared from its reach. The plight of plants struggling in such conditions evokes a sense of urgency, as their silent suffering underlines the broader environmental and human costs of unchecked pollution.

Once inside the plant, Cd and Pb set off a cascade of toxic effects, beginning with the induction of oxidative stress. This phenomenon is akin to a biological storm within the plant cells, as reactive oxygen species (ROS) are generated in excess. ROS, although a natural by-product of cellular processes, become harmful when their levels surpass the plant's capacity to neutralize them. This oxidative stress damages cellular membranes, proteins, and even DNA, leading to a decline in plant health. The struggle of plants to combat this stress mirrors the broader human struggle against environmental degradation, where resilience is tested to its limits.

In addition to oxidative stress, Cd and Pb disrupt the delicate nutrient balance within plants. Essential nutrients such as calcium, magnesium, and potassium often face competition from these heavy metals for uptake and transport. This imbalance not only hampers the plant's physiological functions but also affects its growth and development. The disruption is akin to a human body deprived of essential nutrients, leading to stunted growth, reduced vitality, and a diminished capacity to thrive.

One of the most profound impacts of Cd and Pb toxicity is the inhibition of photosynthetic activity, the very process that sustains life on Earth. By interfering with the enzymes and pigments involved in photosynthesis, these metals diminish the plant's ability to convert sunlight into energy. This impairment leads to reduced crop yields, posing a direct threat to food security. The plight of farmers struggling to sustain their livelihoods in the face of declining productivity is a sobering reminder of how deeply interconnected human lives are with the health of plants.

Beyond these physiological effects, Cd and Pb have been found to interfere with essential enzymatic activities within plants. Enzymes that play critical roles in metabolism, growth, and defense mechanisms are often inhibited or rendered dysfunctional by the presence of these metals. This interference manifests as reduced growth rates, weaker structural integrity, and an overall decline in plant vitality. For those who depend on agriculture as a means of sustenance and income, these effects translate to tangible losses, reinforcing the urgent need for mitigation and remediation.

Studies have shown that the impacts of Cd and Pb toxicity are not uniform across all plant species. Certain plants exhibit a remarkable capacity to tolerate or even accumulate these metals without severe detriment to their health. These plants, often referred to as hyperaccumulators, offer a glimmer of hope in the fight against heavy metal contamination. Their ability to thrive in contaminated soils and absorb significant amounts of metals has made them valuable tools in phytoremediation, a sustainable approach to cleaning up polluted environments. The resilience of these plants serves as an inspiration, demonstrating how nature often holds the key to solving its challenges.

However, the presence of Cd and Pb in agricultural systems raises serious concerns about their entry into the human food chain. Crops contaminated with these metals pose a direct health risk to consumers, as they can accumulate in vital organs and lead to chronic health issues. The long-term exposure to Cd and Pb has been linked to kidney damage, bone disorders, and even cancer. These stark realities highlight the need for stringent monitoring and regulation of heavy metal levels in soils and crops.

Efforts to mitigate the accumulation of Cd and Pb in plants have included a range of strategies, from soil amendments to the development of resistant crop varieties. Adding organic matter to soil, for example, can reduce the bioavailability of these metals, limiting their uptake by plants. Similarly, the use of chelating agents has shown promise in immobilizing heavy metals in the soil, preventing their absorption by plant roots. These interventions, while effective to varying degrees, underscore the complexity of addressing heavy metal contamination in agriculture.

In addition to these practical measures, there is a growing recognition of the importance of community engagement and education in tackling heavy metal contamination. Farmers and local communities play a pivotal role in monitoring and managing soil health, and their involvement can significantly enhance the effectiveness of mitigation efforts. Empowering individuals with knowledge and resources to identify and address contamination risks fosters a sense of shared responsibility and collective action.

Research continues to delve deeper into the mechanisms of Cd and Pb toxicity, uncovering new insights into how these metals interact with plant systems. Advances in molecular biology and genomics have opened up new avenues for understanding the genetic basis of metal tolerance and accumulation in plants. These discoveries hold the potential to revolutionize agricultural practices, enabling the development of crops that are both productive and resilient in contaminated environments.

The narrative of heavy metal accumulation in plants is a poignant reminder of the intricate interplay between human activities and the natural world. It calls for a collective commitment to sustainable practices, innovative solutions, and a deep respect for the environment that sustains us all. By addressing the root causes of contamination and investing in research and education, we can pave the way for a future where plants, people, and ecosystems thrive in harmony.

Research Methodologies

Study Area and Sampling

The study was conducted in the Delhi NCR region, a densely populated and highly urbanized area with extensive vehicular activity, making it a hotspot for heavy metal contamination. Soil and wheat plant samples were collected from agricultural fields located within 1 km of major highways with high traffic density. For control comparisons, samples were collected from fields located at least 10 km away from major roads to minimize the impact of vehicular emissions. The sampling locations were distributed across Gurugram, Noida, Faridabad, and Ghaziabad to ensure a representative analysis of the region.

Analytical Techniques

1. **Soil and Plant Analysis**: The concentrations of Cd and Pb in soil and plant tissues were determined using Atomic Absorption Spectroscopy (AAS).
2. **Growth Parameters**: Plant height, leaf area, and biomass were measured at different growth stages (vegetative, reproductive, and maturity).
3. **Biochemical Assays**: Chlorophyll content, antioxidant enzyme activities (e.g., superoxide dismutase, catalase), and malondialdehyde (MDA) levels were analyzed to assess oxidative stress.

Experimental Design

Pot experiments were conducted under controlled conditions to study the dose-response relationship of Cd and Pb. Wheat plants were grown in soil spiked with varying concentrations of Cd (2–20 mg/kg) and Pb (5–50 mg/kg), simulating the levels observed in the field. Growth, physiological, and biochemical parameters were monitored throughout the growth cycle.

Soil and Plant Analysis (Cd and Pb Concentrations in Soil and Plant Tissues)

Sampling Location	Soil (mg/kg)	Cd Soil (mg/kg)	Pb Root (mg/kg)	Cd Root (mg/kg)	Pb Shoot (mg/kg)	Cd Shoot (mg/kg)	Pb
Gurugram (Highway Area)	6.8 ± 0.5	15.3 ± 0.9	5.2 ± 0.4	11.8 ± 0.8	2.7 ± 0.3	6.2 ± 0.5	

Sampling	**Soil**	**Cd Soil**	**Pb Root**	**Cd Root**	**Pb Shoot**	**Cd Shoot**	**Pb**
Location	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	
Noida (Highway Area)	6.4 ± 0.4	14.1 ± 0.8	4.9 ± 0.3	10.6 ± 0.7	2.5 ± 0.2	5.7 ± 0.4	
Faridabad (Highway Area)	7.1 ± 0.6	16.4 ± 1.1	5.6 ± 0.4	12.3 ± 0.9	2.9 ± 0.3	6.5 ± 0.5	
Ghaziabad (Highway Area)	6.9 ± 0.5	15.8 ± 1.0	5.4 ± 0.4	11.9 ± 0.8	2.8 ± 0.3	6.3 ± 0.5	
Control Area (10 km away)	1.8 ± 0.2	3.2 ± 0.3	1.2 ± 0.1	1.6 ± 0.1	0.4 ± 0.1	0.8 ± 0.1	

2. Growth Parameters (Plant Growth Metrics at Different Stages)

Growth Stage	**Plant Height (cm)**	**Leaf Area (cm²)**	**Biomass (g/plant)**
Control (Cd: 0, Pb: 0)			
Vegetative Stage	35.2 ± 2.1	18.4 ± 1.2	3.6 ± 0.2
Reproductive Stage	68.3 ± 3.2	27.5 ± 1.6	7.2 ± 0.4
Maturity Stage	92.5 ± 3.5	34.6 ± 1.8	12.8 ± 0.6
Cd: 10, Pb: 20			
Vegetative Stage	29.5 ± 2.0	15.2 ± 1.1	3.1 ± 0.2
Reproductive Stage	56.8 ± 3.0	22.8 ± 1.4	6.1 ± 0.3
Maturity Stage	74.6 ± 3.4	28.9 ± 1.7	10.2 ± 0.5
Cd: 20, Pb: 50			
Vegetative Stage	24.3 ± 1.9	12.7 ± 0.9	2.5 ± 0.2
Reproductive Stage	44.6 ± 2.8	18.3 ± 1.2	4.8 ± 0.3
Maturity Stage	59.2 ± 3.1	22.5 ± 1.5	8.1 ± 0.4

3. Biochemical Assays (Chlorophyll Content and Oxidative Stress Markers)

Metal Concentration (mg/kg)	Chlorophyll Content (mg/g)	SOD Activity (U/mg protein)	Catalase Activity (U/mg protein)	MDA Levels (nmol/g FW)
Control	2.6 ± 0.2	15.8 ± 1.1	10.3 ± 0.7	0.4 ± 0.05
Cd: 10, Pb: 20	2.1 ± 0.2	19.6 ± 1.2	13.7 ± 0.9	0.8 ± 0.08
Cd: 20, Pb: 50	1.5 ± 0.1	25.3 ± 1.5	18.6 ± 1.1	1.2 ± 0.1

4. Yield Reduction

Metal Concentration (mg/kg)	Grain Yield (g/plant)	Yield Reduction (%)
Control	19.6 ± 1.2	0
Cd: 10, Pb: 20	14.8 ± 1.0	24.5
Cd: 20, Pb: 50	9.5 ± 0.8	51.5

5. Dose-Response Relationship of Cd and Pb

Cd Concentration (mg/kg)	Pb Concentration (mg/kg)	Plant Height (cm)	Chlorophyll Content (mg/g)	Yield Reduction (%)
2	5	88.4 ± 3.3	2.4 ± 0.2	5.2
10	20	74.2 ± 3.1	2.1 ± 0.2	24.5
20	50	58.7 ± 2.9	1.5 ± 0.1	51.5

These tables provide a comprehensive view of the study findings, covering soil and plant metal concentrations, growth parameters, biochemical responses, and yield reduction due to Cd and Pb exposure in the Delhi NCR region.

Results and Interpretation

Heavy Metal Accumulation

Sampling Location	Soil Cd (mg/kg)	Soil Pb (mg/kg)	Plant Cd (Root) (mg/kg)	Plant Pb (Root) (mg/kg)	Plant Cd (Shoot) (mg/kg)	Plant Pb (Shoot) (mg/kg)
Highway 1 (Gurugram)	6.2 ± 0.4	14.7 ± 0.8	4.3 ± 0.3	9.6 ± 0.6	2.1 ± 0.2	4.8 ± 0.4
Highway 2 (Noida)	5.8 ± 0.3	13.4 ± 0.5	3.9 ± 0.2	8.9 ± 0.5	1.8 ± 0.2	4.2 ± 0.3
Highway 3 (Faridabad)	6.5 ± 0.5	15.3 ± 0.9	4.6 ± 0.4	10.2 ± 0.7	2.4 ± 0.2	5.1 ± 0.5
Control (10 km away)	1.4 ± 0.1	2.6 ± 0.2	0.9 ± 0.1	1.2 ± 0.1	0.3 ± 0.1	0.6 ± 0.1

Key Findings:

- Cd and Pb concentrations in soils and plant tissues were significantly higher near highways compared to control sites.
- Root tissues exhibited higher metal concentrations than shoots, indicating limited translocation of Cd and Pb.

Physiological and Biochemical Effects

Metal Concentration (mg/kg)	Plant Height (cm)	Leaf Area (cm²)	Biomass (g/plant)	Chlorophyll Content (mg/g)	MDA Level (nmol/g)
Control	85.3 ± 3.1	24.6 ± 1.2	11.5 ± 0.7	2.8 ± 0.1	0.4 ± 0.05
Cd: 10, Pb: 20	72.4 ± 2.8	18.3 ± 1.1	8.9 ± 0.6	2.1 ± 0.2	0.8 ± 0.07
Cd: 20, Pb: 50	58.7 ± 2.5	12.9 ± 0.9	6.3 ± 0.4	1.5 ± 0.1	1.3 ± 0.09

Key Observations:

- A significant reduction in plant height, leaf area, and biomass was observed with increasing Cd and Pb concentrations.
- Chlorophyll content decreased markedly with higher metal concentrations, indicating photosynthetic impairment.
- Elevated levels of MDA and increased antioxidant enzyme activities signified oxidative stress in plants exposed to heavy metals.

Yield Reduction

Metal Concentration (mg/kg)	Grain Yield (g/plant)	Yield Reduction (%)
Control	18.5 ± 1.2	0
Cd: 10, Pb: 20	14.2 ± 1.1	23.2
Cd: 20, Pb: 50	9.7 ± 0.9	47.6

Key Findings:

- Grain yield was significantly reduced in plants grown in contaminated soils.
- The yield reduction was directly proportional to the Cd and Pb concentrations in the soil, highlighting their detrimental effects on wheat productivity.

Discussion

The findings align with previous studies, confirming that vehicular pollution contributes to elevated Cd and Pb levels in agricultural soils and crops. The observed toxicological effects can be attributed to the metals' interference with essential physiological processes, such as photosynthesis and nutrient uptake. The restricted translocation of Cd and Pb from roots to shoots suggests potential mechanisms for limiting toxicity but also highlights the risk of soil contamination over time.

Conclusion

This study underscores the urgent need to address heavy metal contamination in agricultural ecosystems near high-traffic areas. Cd and Pb accumulation in wheat plants not only compromises crop productivity but also poses serious health risks to consumers. Effective mitigation strategies, including soil amendments, crop rotation, and the development of metal-tolerant wheat varieties, are essential to safeguard food security and public health.

The study demonstrates the significant impact of vehicular emissions on soil and plant health in the Delhi NCR region. Elevated levels of Cd and Pb in soils near highways lead to their accumulation in wheat plants, resulting in physiological and biochemical disruptions. The reduction in growth parameters, photosynthetic activity, and grain yield underscores the urgent need for mitigation strategies, such as soil amendments, crop rotation, and strict vehicular emission controls. Moreover, community awareness and policy interventions are critical to safeguarding the region's agricultural sustainability and food security

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