Vehicular Pollution and Its Effects on Physical, Chemical, and Biological Characteristics of Plants

Abstract

Vehicular pollution is a substantial global environmental issue that contributes to the degradation of ecosystems and air quality. Pollutants, such as particulate matter, nitrogen oxides, sulphur dioxide, and heavy metals, exert a direct influence on plants, which are crucial for maintaining ecological balance and promoting environmental health. This review examines the physical, chemical, and biological effects of vehicular pollution on plants, with a particular emphasis on the effects on photosynthesis, growth, and ecosystem services. The most significant observations are morphological changes, such as leaf deformation and growth inhibition, biochemical alterations, such as reduced chlorophyll and carotenoid levels, and evident damage, such as necrosis and chlorosis. The interrelated issues posed by pollution are highlighted by the bioaccumulation of heavy metals and the disturbance of soil-plant nutrient cycles. The review emphasizes the function of plants as bioindicators and their capacity for pollution mitigation, with pollution-tolerant species providing solutions for urban greening and ecosystem restoration. Future research should concentrate on the development of sustainable strategies by integrating multidisciplinary approaches, utilizing emerging technologies such as remote sensing and biomarkers, and examining the combined impacts of climate change and pollution.

Keywords: Vehicular pollution, Plant bioindicators, Heavy metal accumulation, Urban air quality, Pollution mitigation

Highlights

- This review examines the impact of vehicular pollution on plants, focusing on physical, chemical, and biological changes that affect their growth, photosynthesis, and overall health.
- It highlights the bioaccumulation of heavy metals in plants, emphasizing their role as bioindicators for monitoring urban air pollution.
- The study underscores the importance of pollution-tolerant plant species in mitigating air pollution and promoting urban green infrastructure.
- Future research directions emphasize interdisciplinary approaches, including remote sensing and biomarkers, to develop sustainable pollution management strategies.

Introduction

Globally, vehicular pollution is a significant environmental concern that is exacerbated by the growing number of motor vehicles. Automobiles emit a diverse selection of contaminants, such as carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOCs), and greenhouse gases (GHGs) like carbon dioxide (CO_2). This emissions have a negative impact on human health, ecosystems, and air quality, as well as contribute to climate change (Kumar *et al*., 2020). The majority of vehicular emissions are generated in urban areas as a result of traffic congestion and high population density. These emissions increase environmental and health hazards by contributing significantly to the formation of smog, ground-level ozone, and the urban heat island effect (Lang *et al*., 2021). Additionally, road transport contributes significantly to global CO_2 emissions, which constitute about 23% of total energy-related emissions globally (Suthaputchakun *et al*., 2012).Vehicular pollution also has significant implications for climate systems, as it affects the depletion of the ozone layer and radiative forcing. The global climate is influenced by the widespread prevalence of nitrogen oxides and particulate matter, which alters atmospheric chemistry and accelerates warming trends (Akimoto, 2003). Vehicular pollution mitigation initiatives encompass the implementation of strict emissions standards, the transition to electric vehicles, and the enhancement of public transportation systems. Nevertheless, challenges continue to exist, notably in developing countries where the rapid urbanization process results in an increase in vehicle usage, which in turn worsens pollution levels (Uherek *et al*., 2010). This global issue underscores the urgency of implementing coordinated international strategies to promote sustainable transportation and reduce vehicular emissions to protect environmental and public health. In order to properly understand the ways in which human activities affect ecosystems and to formulate sustainable strategies to mitigate these effects, it is essential to investigate the effects of vehicular pollution on vegetation. Not only do plants maintain biodiversity, but they also provide essential ecosystem services that are essential for the survival of life on Earth. In order to fully appreciate the profound impact of vehicular pollution on ecological, economic, and environmental systems, it is necessary to investigate the effects of this pollution on vegetation. In addition to their contributions to food security, aesthetics, and climate regulation, plants are critically important in the preservation of air quality, biodiversity, and ecosystem balance. Because of their significance, this subject requires considerable attention. First and foremost, plants are reliable bioindicators of pollution, frequently being the first to demonstrate changes in response to environmental stress.

Physiological and biochemical changes, including reduced photosynthetic rates and chlorophyll degradation, offer critical insights into air quality conditions (Muthu *et al*., 2021). The second factor is that vehicular emissions have significant effects on photosynthesis and growth. Traffic exposure is associated with reduced chlorophyll content and impaired physiological functions. As a consequence of these modifications, ecological productivity is diminished (Durrani *et al*., 2004). Additionally, the capacity of plants to support biodiversity and ecosystem services is negatively impacted by the accumulation of contaminants such as heavy metals and particulate matter. This is particularly critical in urban areas, where roadside plants act as protections for the environment (Altaf *et al*., 2021). These responses can assist in urban planning and environmental management strategies, including the selection of pollution-tolerant plant species for urban greening to enhance their efficacy as natural pollution mitigators (Singh *et al*., 2020). In addition, the efficiency of plants in reducing air pollutants is influenced by vehicular pollution, which in turn elevates the health risks for humans and other species. This interconnectedness underscores the importance of conducting additional research to alleviate these effects (Bisht *et al*., 2016). The primary objective of this review paper is to investigate and summarize the effects of vehicular pollution on the physical, chemical, and biological characteristics of plants. This knowledge is essential for addressing the broader ecological, economic, and environmental consequences of vehicular emissions, particularly in the context of urbanization and climate change. The paper's scope includes three critical dimensions of plant responses to vehicular pollution: physical alterations, chemical disruptions, and biological impacts (e.g., oxidative stress, changes in microbial associations). It also explores the extent to which these effects vary across spatial and temporal contexts, thereby facilitating a more profound understanding of the time-dependent dynamics that are unique to a specific region. By addressing these dimensions, the review provides a comprehensive perspective on the multifarious challenges presented by vehicular pollution. It also highlights the potential of plants to enhance urban greening and environmental management by acting as bioindicators and mitigators of air pollution. The study also identifies gaps in current research, such as the need for multidisciplinary approaches, advanced assessment technologies like remote sensing, and investigations into the interplay between pollution and climate change.

2)Overview of Vehicular Pollution

Vehicular pollution is a substantial contributor to environmental degradation and emits a variety of harmful pollutants that have an adverse effect on plants. Carbon monoxide, a colourless and inert gas that is generated by incomplete combustion, disrupts the biological process of oxygen absorption, which poses a threat to the health of plants (Nagpure *et al*., 2016). Nitrogen oxides from vehicular emission react in the atmosphere to produce secondary pollutants such as ozone and nitrate aerosols, which limit photosynthesis and damage plant tissues (Platt *et al*., 2017). Sulphur dioxide, a byproduct of combustion of sulphur-containing fuels, contributes to acid rain, modifying soil chemistry and reducing nutrient availability (Sindhwani and Goyal, 2014).Particle matter accumulates on plant surfaces, obstructing gas exchange and clogging stomata, thereby affecting photosynthesis and growth. Additionally, it serves as a carrier for toxic heavy metals (Zhang *et al*., 2020a). The formation of ground-level ozone is facilitated by volatile organic compounds, which are released from fuel evaporation and exhaust. This process results in foliar injury and a decrease in crop yields (Sindhwani and Goyal, 2014). Ultimately, the health and productivity of plants have been harmed by the adverse effects of these pollutants on their physical, chemical, and biological characteristics. The combustion of fossil fuels in internal combustion engines is the primary source of vehicular pollution, which results in the release of a variety of pollutants through intricate chemical reactions. Incomplete combustion, which occurs when hydrocarbons in the fuel are not entirely oxidized, is one of the primary contributors to pollution. This leads to the emission of carbon monoxide, unburned hydrocarbons, and particulate matter, all of which have significant impacts on human health and air quality (Ogunkunle and Ahmed, 2021). Furthermore, the high temperatures within engines induce the reaction between nitrogen in the air and oxygen, resulting in the production of nitrogen oxides. These oxides are responsible for pollution, acid rain, and other environmental challenges (Thomas, 1997). Diesel engines are notable for the production of fine particulate matter as a result of incomplete fuel atomization and combustion. These particles present substantial health hazards due to their ability to penetrate the lungs at a profound level (Morawska and Zhang, 2002). Additionally, vehicles emit volatile organic compounds, which are precursors to ground-level ozone and exacerbate air quality issues (Gaffney and Marley, 2009). In addition to gaseous pollutants, combustion releases toxic chemicals such as benzene and heavy metals like lead, cadmium, and zinc, all of which have negative environmental and health consequences (Chen *et al*., 2019). The most prominent greenhouse gas is carbon dioxide, which is also substantially contributed to by vehicular emissions. The transportation sector is responsible for approximately 24% of global emissions from fossil fuels (Ogunkunle and Ahmed, 2021). Additionally, the combustion of sulphur-containing fuels results in the emission of sulphur dioxide, which, in conjunction with NOx, can contribute to acid rain and other forms of environmental degradation (Wójtowicz *et al*., 1993). In order to reduce vehicular pollution, it is necessary to transition to advanced combustion technologies and greener energy sources. For instance, hydrogen and biodiesel supplementation have been demonstrated to significantly decrease emissions of particulate matter, NOx, and other harmful pollutants (Sharma and Dhar, 2018). Additionally, oxygen-enriched combustion technologies can enhance fuel efficiency while reducing pollutant levels (Baskar and Senthilkumar, 2016). Significant progress can be achieved in the reduction of the environmental and health effects of vehicular emissions by understanding the mechanisms of pollutant release and implementing these strategies. The effects of vehicular pollution on the physical, chemical, and biological characteristics of plants are substantially different in urban and rural areas, and they fluctuate with seasonal differences. High concentrations of pollutants, including nitrogen oxides and particulate matter, induce significant stress on plants in urban environments, leading to a decline in chlorophyll content, protein levels, and overall physiological health. These regions frequently experience substantial biochemical changes as a result of their direct and intense exposure to vehicular emissions. In contrast, rural plants are subjected to lower levels of pollution; however, contaminants from urban areas, such as nitrogen oxides, can still travel to these regions, resulting in mild but measurable effects on plant health. Research has shown that plants in urban environments frequently exhibit a higher tolerance index than their rural counterparts as a result of adaptive mechanisms. This suggests that urban plants develop resilience to deal with elevated pollution levels (Mansfield and Freer-Smith, 1981) (Shakeel *et al*., 2023). The extent of pollution's impact is further influenced by seasonal variations. Reduced atmospheric dispersal and lower temperatures during winter result in the accumulation of pollutants, which has more severe effects on plants, including increased lead deposition and greater reductions in chlorophyll levels. Conversely, the monsoon season typically reduces the negative impact of pollutants on vegetation by diluting them through rainfall. Conversely, the formation of pollutants, particularly ozone, gets worse during the summer, which disrupts photosynthetic processes and increases oxidative stress in plants ((Honour *et al*., 2009). In urban environments, specific plant species have been observed to exhibit mitigation adaptations. Grevillea robusta and Mangifera indica are examples of species that exhibit robust resilience and adaptation. They have the potential to absorb pollutants and improve water use efficiency, rendering them appropriate for urban planting to mitigate the effects of vehicular pollution. These species exhibit a greater tolerance to contaminants, which indicates their potential to reduce the effects of air pollution and promote the development of urban green space. The interaction between urban and rural dynamics, together with seasonal variations, emphasizes the complex nature of vehicle pollution effects on plant systems, highlighting the necessity for specific interventions and adaptive urban landscaping to mitigate these effects.

3) Physical Impacts of Vehicular Pollution on Plants

The physical effects of vehicular pollution on plants are significant as evidenced by visible damage such as necrosis, chlorosis, and leaf discoloration. Research has demonstrated that plants located in high-traffic areas frequently exhibit these symptoms, including chlorosis, leaf burning, and pigmentation changes. These symptoms are directly associated with increased exposure to vehicular emissions. Examples of such plants include *Ficus bengalensis* and *Alstonia scholaris* (Nandy *et al*., 2014). Furthermore, under simulated pollution conditions, species such as *Spondias purpurea* have been observed to experience severe necrosis and chlorosis as a result of contaminants like fluoride, a frequent byproduct of vehicular emissions (Anjos *et al*., 2018). Another pollutant associated with vehicular emissions, sulphur dioxide, has been discovered to degrade chlorophyll, resulting in chlorosis and structural damage to chloroplasts. This contributes to the decline in plant health (Psaras and Christodoulakis, 1987). Environmental conditions can intensify these effects; for example, high light intensity can worsen chlorosis and necrosis in nutrient-deficient plants suffering from pollution stress (Marschner and Cakmak, 1989). Furthermore, the growth and vitality of plants are adversely affected by roadside dust, which is a frequent consequence of vehicular activity. This dust reduces chlorophyll content, resulting in leaf discoloration, decreased photosynthesis, and necrosis (Shah *et al*., 2018). These consequences emphasize the urgent necessity of addressing vehicular pollution in order to preserve the health of plants and preserve ecological balance. The morphology of plants is significantly influenced by vehicular pollution, which results in reduced leaf size, deformation, and growth inhibition. These modifications are the consequence of exposure to contaminants, including particulate matter, heavy metals, and gases such as sulphur dioxide and nitrogen oxides, which disrupt physiological processes and impart visible damage on plant structures. For example, soybean plants that were subjected to acid rain and gaseous contaminants exhibited notable leaf deformation and decreased growth. This effect was primarily caused by a decrease in the leaf area ratio, which was attributed to morphological changes (Norby and Luxmoore, 1983). Vehicular pollution and other stressors, such as drought, further worsen these morphological damages. The compounded impact on plant health was demonstrated by the earlier leaf yellowing, premature shedding, and reduced leaf mass per area that urban plants exhibited in response to these conditions (Lin *et al*., 2021). In addition, emissions from cement industries, containing dust and harmful gases, have been linked to reduced leaf stomatal conductance, visible leaf injuries, and an overall decline in leaf size and plant yield (Chaurasia *et al*., 2014). Vehicular pollution presents considerable morphological problems to plants, hindering their growth, functionality, and ecological importance. Mitigating these effects is crucial for preserving the vitality and production of plants in polluted environments. The deposition of dust and particle matter substantially affects the photosynthetic and stomatal function of plants, resulting in diminished productivity and physiological stress. The buildup of dust on leaves hinders light penetration, distorting the photosynthetic machinery and diminishing photosynthesis rates. The impact is intensified by smaller dust particles, which produce a more significant shade effect, especially in low-light settings (Yamaguchi and Izuta, 2017). During the light period, dust physically blocks the openings, thereby reducing gas exchange and interfering with stomatal function. This obstruction restricts the absorption of CO_2 that is essential for photosynthesis and increases water loss at night as a result of poor stomatal closure (Hirano *et al*., 1991); (Squires, 2016). Dust can have a chemical and thermal impact on plant function, in addition to its physical effects. It has the potential to alter the temperature of the leaf surface by absorbing heat, which can have a varying impact on photosynthesis based on whether the ambient temperature is above or below the plant's optimal level. Additionally, the chemical components of dust, such as pH or toxic particles, may worsen these effects, resulting in stress and injury (Ibrahim and El-Gaely, 2012). Species-specific reactions to dust deposition are significant, exhibiting variations influenced by leaf surface features and adaptive qualities. For instance, plants with thick ribs and pubescent leaves could see more noticeable decreases in gas exchange than plants with smoother leaves (González *et al*., 2014). The extent of dust accumulation is influenced by leaf morphology, including roughness, orientation, and presence of waxy coatings. Plants with rough surfaces, short petioles, and folded margins tend to accumulate more particulate matter than those with smooth and flat surfaces. This deposition not only alters leaf architecture but also reduces leaf area and petiole length, leading to thinner leaves in plants growing in highly polluted areas (Pandit and Sharma, 2020).

4) Chemical Impacts of Vehicular Pollution on Plants

The photosynthetic pigments of plants, notably chlorophyll and carotenoids, which are essential for photosynthesis and plant health, are significantly affected by vehicular pollution. Research consistently demonstrates that vehicular emissions considerably reduce the chlorophyll content of plants, including chlorophyll-a, chlorophyll-b, and total chlorophyll. For example, a study examining roadside trees found reductions in total chlorophyll content by up to 48.73% in Holoptelea integrifolia, while Mallotus philippinensis experienced a smaller but notable reduction of 17.84% (Joshi and Swami, 2009). A similar trend was observed in landscape plants, as chlorophyll levels decreased in response to elevated dust exposure, with species-specific variations. In urban areas with heavy traffic, plants consistently exhibited reduced chlorophyll content, underscoring the direct impact of vehicular emissions on plant physiology (Iqbal *et al*., 2015). Decreased carotenoid concentrations were noted in Calotropis procera, a species frequently utilized as a biomonitor, indicating significant oxidative stress induced by roadside pollution (Hadayat *et al*., 2018). Continuous exposure to pollutants like dust also disrupts the biosynthesis of carotenoids, affecting the overall pigment profile and plant health (Mandre and Tuulmets, 1997). The mechanistic effects of vehicular pollutants, including heavy metals and particulate matter, involve the degradation of existing pigments and the inhibition of pigment biosynthesis through oxidative stress. Plants located in proximity to high-traffic areas are particularly susceptible to these disruptions, which impede their growth and photosynthetic efficiency. These studies collectively emphasize the fact that vehicular pollution results in major reductions in chlorophyll and carotenoid levels, which subsequently hinders the photosynthetic performance and overall vitality of plants. These pigment modifications not only affect the health of plants but also function as critical indicators of environmental pollution levels. Vehicular pollution has a profound impact on the chemical interactions between soil and plants, which has significant implications for soil chemistry and nutrient assimilation. Vehicular emissions contribute to the accumulation of pollutants, including heavy metals (e.g., lead, cadmium, and zinc), in roadside soils, which disrupts essential nutrient cycling processes and modifies their chemical composition. This results in reduced soil fertility and impaired plant growth, as plants exposed to polluted environments exhibit changes in root exudates that mobilize heavy metals, which can interfere with the absorption of essential nutrients (De Silva *et al*., 2021), (Cataldo and Wildung, 1978). Microbial communities in contaminated soils experience shifts impacting essential activities like nitrogen fixation and phosphorus solubilization. Although certain bacteria acquire resistance to heavy metals, this adaptation can reduce the bioavailability of essential nutrients for plants. Furthermore, the interaction of pollutants like phosphorus and arsenic illustrates how competitive adsorption and transport mechanisms may restrict nutrient efficiency (Adesemoye and Kloepper, 2009), (Wu *et al*., 2021) . Moreover, pollutants disrupt the nutrient balance and root absorption mechanisms of plants, thereby affecting their physiological processes. For example, heavy metals like lead can imitate essential ions like calcium, resulting in systemic imbalances and the interference with the uptake of nutrients. Nanoparticles and airborne pollutants also affect plants by disrupting water and nutrient transport mechanisms, which can result in a decrease in photosynthetic activity and overall growth (Pingfan *et al*., 2022). Phytoremediation and rhizoremediation have been demonstrated to be effective in reducing soil contamination in order to mitigate these effects. These methods can enhance soil health, restore nutrient cycling, and detoxify polluted soils by utilizing plant-microbe interactions. The utilization of organic amendments and microbial inoculants further improves soil fertility and facilitates the sustainable absorption of nutrients in highly stressed environments (Vergani *et al*., 2017), (Vimal *et al*., 2017).The physical, chemical, and biological characteristics of plants are significantly impacted by the toxicity of heavy metals that result from vehicular pollution. Heavy metals, including lead (Pb), cadmium (Cd), and zinc (Zn), are non-biodegradable pollutants that accumulate in the environment, resulting in bioaccumulation in plants. This process has the potential to significantly impact the ecological balance and the health of plants. For example, research on plants such as Plantago major has shown that these species are capable of absorbing and translocating heavy metals from the soil. Metal concentrations are significantly reduced at greater distances from pollution sources, such as highways. These plants are logical choices for phytoextraction, a procedure that involves the removal of contaminants from the environment using plants, due to the high translocation factors of metals such as Cd and Pb (Galal and Shehata, 2015). Roadside vegetation, such as *Acacia nilotica* and *Ziziphus mauritiana*, has been shown to accumulate significant amounts of heavy metals from vehicular emissions. These species not only mitigate pollution but also highlight the potential of wild plants in pollution control efforts near roadsides (Altaf *et al*., 2021). Nevertheless, bioaccumulation has severe repercussions for plants. Abnormal growth, reduced biomass, and reproductive malformations may result from increased heavy metal concentrations in the soil. For instance, the adverse effects of synergistic heavy metal toxicity were evident in the stunted growth and malformations of reproductive structures of maize (*Zea mays*) that was exposed to such conditions in the immediate area of mining areas (Ruiz-Huerta *et al*., 2021). The growth inhibition and reduced biomass production in plants are common symptoms of physiological stress caused by heavy metals, such as Cd, Pb, and Zn. Halophytes, such as Atriplex hortensis, exhibit a significant decrease in biomass when exposed to heavy metals, which highlights the negative impacts of these pollutants on plant physiology (Kachout *et al*., 2009). Additionally, the introduction of heavy metals into plants can result in their eventual entry into the food chain, which poses significant health risks and ecological hazards. The long-term effects of these pollutants are a cause for concern, as they disrupt plant functions and destabilize ecosystems (Briffa *et al*., 2020). Despite these challenges, some plant species with high bioaccumulation capacities, such as *Betula pendula* and *Taraxacum officinale*, can serve as bioindicators for environmental monitoring. Their ability to absorb heavy metals makes them effective tools for assessing contamination levels in polluted urban areas (Nadgórska-Socha *et al*., 2017) 55. Consequently, understanding and applying the bioaccumulation properties of plants can assist in reducing pollution effects, enhancing environmental health, and preserving ecosystem stability.

5) Biological Impacts of Vehicular Pollution on Plants

In plants, oxidative stress arises when there is an imbalance between the production of reactive oxygen species (ROS) and the plant's capacity to detoxify them or repair the consequent damage. ROS levels, including superoxide anions, hydrogen peroxide, and hydroxyl radicals, are significantly elevated by vehicular pollution, which contributes to this stress. Although these reactive molecules are naturally produced as metabolic byproducts, they can become harmful under stress conditions, resulting in damage to DNA, proteins, and lipids. Nevertheless, ROS also serve as secondary messengers in cellular signaling, modulating gene expression and stress response pathways (Sharma *et al*., 2012). In order to mitigate the adverse effects of reactive oxygen species (ROS), plants have developed an advanced antioxidant defense system. This system is composed of enzymatic antioxidants, including catalase (CAT), superoxide dismutase (SOD), and ascorbate peroxidase (APX), which function sequentially to neutralize reactive oxygen species (ROS). For example, SOD catalyzes the breakdown of superoxide radicals into hydrogen peroxide, which is subsequently decomposed into water and oxygen by CAT and APX (Alscher *et al*., 2002). Non-enzymatic antioxidants such as ascorbate, glutathione, carotenoids, and tocopherols complement this enzymatic machinery, directly scavenging ROS and regenerating antioxidant molecules to maintain cellular redox balance (Hasanuzzaman *et al*., 2019). However, ROS also function as signaling molecules that initiate the activation of antioxidant genes and stress adaptation mechanisms, despite their destructive potential. This dual function emphasizes the significance of preserving a delicate equilibrium between the production of reactive oxygen species (ROS) and their scavenging. The antioxidant defenses are overpowered by increased ROS levels, which results in oxidative damage, such as DNA fragmentation and lipid peroxidation. Alternatively, the normal metabolic processes and stress signaling are dependent upon low or moderate ROS levels (Scandalios, 2005). In a nutshell it is essential to understand the interaction between antioxidant defense mechanisms and reactive oxygen species (ROS) in order to mitigate the effects of vehicular pollution on vegetation. The development of sustainable strategies to mitigate the adverse effects of oxidative stress can be facilitated by the enhancement of these defense systems, which can increase the resilience of plants to environmental stressors (Soares *et al*., 2019). The growth and development of plants, as well as their root-shoot ratios, flowering, and fruiting patterns, are all significantly affected by vehicular pollution. Root-shoot allocation is impacted by pollutants such as sulphur dioxide, ozone, nitrogen oxides, and particulate matter, which inhibit root growth in comparison to shoots. For example, oxidative stress and impaired nutrient absorption frequently result in a decreased root-to-shoot (R:S) ratio when shoot growth persists and root biomass is reduced by exposure to Ozone (Rogers *et al*., 1995). Similarly, PM accumulation inhibits root elongation and dry matter accumulation, further disrupting the balance between root and shoot growth (Daresta *et al*., 2015). Vehicular pollution also has an adverse effect on flowering patterns, primarily through hormonal disruptions and reduced photosynthetic efficiency. For instance, the adverse effects of ozone exposure on plant physiology and reproductive development result in the delay of flowering and a reduction in flower production in numerous plant species (Honour *et al*., 2009). Additionally, pollutants can indirectly impact flowering by depleting soil boron levels, which are crucial for pollen viability and reproductive success (Dell and Huang, 1997). A significant reduction in fruit number, size, and quality is evident in the fruiting patterns, which are particularly susceptible to vehicular pollution. Reduced crop productivity and decreased fruit yields are the result of ozone exposure, which impairs reproductive processes such as pollen germination, ovule development, and seed viability (Leisner and Ainsworth, 2012). Moreover, PM deposition can influence the biochemical properties of fruits, such as sugar-to-acid ratios, which are critical for fruit quality and marketability (Thwe *et al*., 2020). The delicate balance of soil ecosystems is considerably impacted by vehicular pollution, with a particular emphasis on nitrogen-fixing bacteria and mycorrhizal fungi. These two microbial groups are essential for the enhanced absorption of nutrients and the growth of plants. Mycorrhizal fungi enhance phosphorus assimilation, while nitrogen-fixing bacteria fix atmospheric nitrogen, thereby providing essential nutrients, particularly in phosphorus-deficient soils. The synergistic interaction between these microorganisms is essential for the health and resilience of plants, as evidenced by studies that demonstrate that co-inoculation improves plant biomass, nitrogen assimilation, and phosphorus absorption, even in nutrient-poor or contaminated environments (Barea *et al*., 1992), (Miyauchi *et al*., 2008). Mycorrhizal fungi maintain antioxidant activity and nutrient cycling in the presence of adverse conditions, such as drought, while nitrogen-fixing bacteria further enhance plant resilience. Together, they enhance plant productivity, even in the presence of abiotic stresses, indicating their potential for sustainable agriculture in challenging environments (Goicoechea *et al*., 2005).

6. Case Studies and Regional Analyses

The effects of vehicular pollution on plants are considerably different in urban and rural areas, particularly when comparing regions with high and low traffic intensity. Research has demonstrated that urban areas with high traffic volumes experience increased concentrations of pollutants, including polycyclic aromatic hydrocarbons (PAHs) and particulate matter (PM_{10}), which result in severe soil and air contamination. For example, soils in rural areas contained 21 times fewer carcinogenic PAHs than soils in urban areas near high-traffic areas, according to research conducted in Delhi, India. Urban sites were characterized by high molecular weight PAHs that were associated with vehicular emissions, while rural areas exhibited lower molecular weight PAHs, which indicated a decrease in traffic-related contamination (Agarwal, 2009). In high-traffic urban environments, plants become bioindicators when they are exposed to such pollution, as their physiological and biochemical parameters are significantly altered. Roadside plants in Jalgaon, India, exhibited a significant decrease in leaf area, chlorophyll content, and protein levels when compared with those in less polluted rural areas, according to research. These modifications emphasize the detrimental effects of vehicular emissions on the heath of plants (Wagh *et al*., 2006). Likewise urban regions in Kathmandu, Nepal, noticed substantial increases in PM_{10} concentrations, particularly in high-traffic areas. The central role of vehicular emissions in the degradation of air quality is underscored by the fact that pollution levels decreased during temporary traffic shutdowns, but they soon reverted (Fransen *et al*., 2013). Plants in high-traffic metropolitan areas frequently evolve adaptations to reduce pollution stress, such as increased leaf thickness and water efficiency. However, these adaptations are frequently insufficient to combat damage, as demonstrated by a research in Qingdao, China, where significant reductions in photosynthetic rates and evident leaf damage were detected in urban plants compared to those in rural environments (Cui *et al*., 2006). Furthermore, the use of biomonitors, such as *Tillandsia recurvata*, has been helpful in determining pollution levels. These air plants accumulate heavy metals in urban high-traffic zones, which correlate closely with vehicular density, making them useful tools for monitoring urban air quality (Piazzetta *et al*., 2018). In general, the effects of vehicular pollution are significantly more severe in urban areas with high traffic than in rural regions. The pressing need for precise urban planning and pollution mitigation strategies is emphasized by the resulting soil and air contamination, as well as the altered physiological responses of plants. Additionally, the deployment of bioindicator plants offers a valuable means to monitor and address these environmental challenges. Longitudinal investigations have demonstrated that continuous exposure to vehicular pollution has considerable time-dependent effects on plant physical, chemical, and biological properties. Pollutants like ozone and nitrogen oxides slow plant growth and impair photosynthetic efficiency. For example, research on Norway spruce revealed no significant early impact, but Sitka spruce showed delayed growth decreases and permanent damage following continuous ozone exposure (Lucas and Diggle, 1997). Similarly, long-term exposure to airborne pollutants such as sulphur dioxide and hydrogen fluoride can reversibly depress CO_2 uptake, but higher pollutant concentrations or extended durations lead to irreversible cellular damage (Bennett and Hill, 1973). Plants also undergo biochemical stress responses as a result of prolonged exposure to vehicular emissions. For instance, stress markers, such as proline content, increase as a protective mechanism, while soluble sugar levels decrease, suggesting that photosynthesis is inhibited during pollutants stress (Agbaire, 2016). Additionally, heavy metals like lead and cadmium, commonly deposited by vehicular emissions, accumulate in plant tissues over time, affecting root and leaf functions and overall plant health (Sapkota and Cioppa, 2012). These morphological and anatomical adaptations are frequently accompanied by chemical and physiological changes. Furthermore, the impacts of chronic pollution extend to reproductive health. The genetic diversity of plant populations has changed and seed viability is reduced as a result of persistent exposure to ozone and other pollutants. This suggests a long-term ecological impact and the potential for genetic adaptation to stress (Black *et al*., 2000). In general, these longitudinal studies emphasize the cumulative and progressive impacts of vehicular pollution on plants. The results highlight the immediate necessity of implementing measures to safeguard plant ecosystems from long-term harm and reduce vehicular emissions. It is essential to understand the variation in tolerance and sensitivity among plants by examining species-specific responses to vehicular pollution. Diverse physiological, biochemical, and morphological adaptations or sensitivities to pollution are exhibited by various species, which are influenced by the type of pollutant, environmental conditions, and inherent genetic characteristics. For instance, a study that compared Datura alba and Ricinus communis along polluted roads revealed that *Datura alba* and *R. communis* both experienced reduced photosynthetic rates and stomatal conductance. However, R. communis exhibited higher tolerance through increased antioxidant activity and free amino acid production. This emphasizes its resistance to urban air pollution in comparison to *D. alba* (Khalid *et al*., 2019). Likewise, roadside trees, including Grevillea robusta and Mangifera indica, exhibited specific adaptive characteristics, such as enhanced water use efficiency and dust removal efficiency, enabling them to mitigate the adverse effects of vehicular emissions. Their suitability for urban green initiatives that are designed to control pollution is emphasized by these characteristics (Singh *et al*., 2020). Herbaceous plants also exhibited varying degrees of sensitivity, with some species showing resilience and others experiencing substantial oxidative stress. This was demonstrated by increased peroxidase activity and reduced chlorophyll content in response to particulate matter (Kováts *et al*., 2021). Additionally, tolerance of species such as *Alstonia scholaris* was evaluated using morphological and biochemical indicators, including leaf thickness, relative water content, and biochemical adaptations (e.g., proline and ascorbic acid levels). This species has exhibited a high degree of adaptability and tolerance to vehicular pollution, which has facilitated its use in roadside plantations (Singh, 2021). In another study of metabolic responses, it was discovered that plant species demonstrate highly specific modifications in their phytometabolomes in response to environmental stress. These metabolic alterations, which are the result of evolutionary adaptation, illustrate the significance of selecting pollution-tolerant species based on their different biochemical profiles (Schweiger *et al*., 2014). The physiological, biochemical, and morphological characteristics of plants contribute to the significant difference in their tolerance and sensitivity to air pollution that is species-specific. Plants with leaves that are rough, waxy, or folded accumulate a greater amount of particulate matter, rendering them effective pollution mitigators. As a defense mechanism, tolerant species experience an increase in biochemical parameters, such as ascorbic acid levels, whereas sensitive species experience a decline, resulting in oxidative stress. In sensitive species, the chlorophyll content, which is crucial for photosynthesis, decreases more considerably, whereas tolerant species maintain higher levels, thereby ensuring resilience. The pH of leaf extracts decreases in sensitive plants as a result of acidic pollutants, whereas tolerant species maintain neutral or alkaline pH, which facilitates stress management. This variability demonstrates the necessity of selecting species that are tolerant to pollution in order to facilitate urban greening initiatives. Plants that are capable of maintaining a balance between water and nutrients in polluted environments exhibit superior stress tolerance. These results illustrate the critical role of species-specific attributes in reducing the effects of air pollution.

7. Mitigation and Management Strategies

Urban vegetation is essential in reducing the effects of vehicular pollution by facilitating pollutant absorption, deposition, and dispersion. Trees and plants function as natural purifiers, removing gaseous pollutants and particulate matter from the atmosphere. For instance, vegetation with a high Air Pollution Tolerance Index (APTI) has been demonstrated to be particularly effective in absorbing contaminants, rendering it a critical element of green belt planning (Kanwar *et al*., 2016). Moreover, green roofs and roadside vegetation barriers are crucial in trapping fine particulate matter on leaf surfaces, with specific species exhibiting enhanced pollutant-removal efficiency (Speak *et al*., 2012). Through stomatal assimilation and surface deposition, vegetation also contributes to the reduction of gaseous pollutants, including ozone (O_3) and nitrogen dioxide (NO_2). The effectiveness of this process is dependent upon the selection of tree species and their physiological characteristics, emphasizing the significance of careful species selection in urban planting initiatives (Nemitz *et al*., 2020). Green belts are further improved in their capacity to trap pollutants and improve air quality by incorporating optimal structural characteristics, such as dense canopies, complex morphology, and high leaf surface area. For instance, roadside vegetation barriers significantly reduce PM concentrations, particularly when they are designed with species that exhibit high pollutant interception capabilities (Tong *et al*., 2016). Urban vegetation offers diverse environmental and health advantages, in addition to pollution mitigation. The exposure to harmful pollutants is reduced, which reduces heat stress and enhances respiratory and cardiovascular health by mitigating the urban heat island effect (Van Ryswyk *et al*., 2019). Incorporating vegetation into urban planning, such as through green roofs, parks, and roadside green belts, not only improves air quality but also enhances urban sustainability, aesthetics, and biodiversity (Ferrini *et al*., 2020). Creating healthier and more habitable cities while addressing the challenges posed by vehicular pollution can be achieved through thoughtful urban planning that prioritizes vegetation. In order to mitigate the effects of vehicular pollution on plants, mitigation and management strategies include the implementation of innovative green infrastructure planning, pollution-tolerant species, and vegetative barriers. Species with dense foliage and high dust retention capacity are particularly effective at filtering particulate matter and gaseous pollutants, as demonstrated by vegetative barriers like roadside plantations and green roofs. Research has demonstrated that species such as Mangifera indica and Grevillea robusta have a high APTI, which makes them suitable for urban and roadside greening initiatives. The superior particulate matter deposition capabilities of cypress species have been demonstrated in studies, which also suggest that strategic vegetation placement, such as tree-shrub configurations or planting along windward or leeward sides of streets, enhances pollutant capture (Zhang *et al*., 2020b).Constructed wetlands and vegetated drainage channels are examples of integrated vegetative approaches that provide more advantages. By utilizing biofiltration mechanisms, these systems not only improve pollutant retention but also facilitate the degradation of harmful substances. Furthermore, the utilization of phytoremediation techniques, which involve the absorption of pollutants such as heavy metals and organic compounds, has demonstrated potential in the reduction of ecotoxicological hazards in polluted environments. This has been documented through the use of plants like duckweed (Kumwimba *et al*., 2018), (Reinhold and Aryal, 2011). For effective implementation, it is essential to identify species that are tolerant to pollution. It has been demonstrated that high-APTI species, including *Mangifera indica*, *Holoptelea integrifolia*, and *Pongamia pinnata*, are effective in pollution mitigation and serve as bioindicators for air quality monitoring. These species exhibit resilience to pollutants and contribute to the vegetation of urban areas by absorbing harmful gases and particulate matter. Many studies underscore the significance of selecting the most suitable species and configurations to optimize the removal of pollutants and the cooling effects of urban areas (Kapoor and Ak, 2016). In order to mitigate vehicular pollution and its detrimental consequences for the physical, chemical, and biological characteristics of plants, emission standards and their enforcement are essential. Strong monitoring and enforcement mechanisms are essential for the successful implementation of regulatory policies. According to research, the mere threat of inspections and regular inspections can substantially reduce emissions while simultaneously promoting accurate self-reporting of pollution levels. In Quebec's pulp and paper industry, for instance, research revealed that frequent inspections not only decreased emissions but also enhanced the reliability of reported data (Laplante and Rilstone, 1995). Self-reporting systems, in conjunction with financial penalties, further improve compliance. In China, the pollution levy system revealed the effectiveness of progressive financial penalties and self-reporting mechanisms in reducing emissions, despite operating in difficult conditions (Wang and Wheeler, 2005). Similarly, the adoption of stricter emission standards, such as those for thermal power plants, has resulted in significant decreases in pollutants like sulphur dioxide and particulates, as demonstrated in Shandong Province, China, where emissions fell drastically after amendments to regulatory standards (Yuan *et al*., 2017). Financial incentives and penalties are also crucial components of efficient regulation. It has been demonstrated that the integration of these mechanisms with legal enforcement results in superior pollution control outcomes. Nevertheless, the issue of enforcement variability across various regions is an important challenge. The effectiveness of enforcement strategies is considerably influenced by local conditions, such as the potential for environmental damage and the dynamics of the labor market. Consequently, the importance of localized approaches is highlighted (Dion *et al*., 1997).

8) Research Gaps and Future Directions

Significant research gaps and opportunities for future exploration are revealed by the investigation of the effects of vehicular pollution on plants. A primary lacuna is the absence of multidisciplinary studies that integrate the physical, chemical, and biological aspects of pollution. The current research frequently isolates these domains, resulting in a fragmented comprehension of the interactions between particulate deposition, chemical alterations, and physiological responses. The integration of these perspectives is essential for a comprehensive understanding of the cumulative effects of pollution on the plant system. Furthermore, the complex nature of vehicular pollution is not adequately captured by conventional assessment methods. Biomarkers, such as chlorophyll degradation, antioxidant responses, and secondary metabolite levels, and remote sensing are emerging technologies that provide advanced, non-invasive, and scalable methods for monitoring the effects of pollution (Hadayat *et al*., 2018). These tools are expected to enhance assessments and provide guidance on mitigation strategies. Understanding the interaction between pollution and climate change is another critical area. Although both impact plant health independently, their combined effects such as elevated temperatures exacerbate pollution stress remain unexplored. Research on this dual stressor is indispensable for the purpose of predicting and mitigating the effects of future climate scenarios (Rai, 2016). Furthermore, the majority of research concentrates on the immediate results and specific plant species, resulting in a substantial void in our understanding of the long-term and ecosystem-level implications. In order to assess the long-term effects of vehicular pollution on plant communities, ecosystem services, and trophic dynamics, chronic exposure studies are required (Shakeel *et al*., 2021). Finally, there is an urgent need to convert scientific discoveries into policy recommendations that can be implemented. The quantification of pollution thresholds that damage plant health and ecosystem integrity can inform environmental regulations, greenbelt design, and urban planning. It is possible to identify and promote plants with high tolerance indices for urban greening initiatives (Muthu *et al*., 2021). Addressing these gaps with multidisciplinary, technology-driven, and policy-oriented research will be vital for mitigating the impacts of vehicular pollution on plants and ecosystems effectively.

9) Conclusion

The physical, chemical, and biological characteristics of plants are significantly affected by vehicular pollution, which has far-reaching implications for human well-being, biodiversity, and ecosystems. This review emphasizes the disruption of plant growth, photosynthesis, and nutrient absorption by pollutants such as particulate matter, nitrogen oxides, and heavy metals, as well as the resulting morphological and biochemical changes. These effects endanger the essential ecosystem services that plants offer, such as biodiversity support, climate regulation, and air purification. Although pollutants can travel and affect vegetation in remote regions, urban environments, where vehicular emissions are most concentrated, show up more severe impacts on plants than rural areas. The complexity of these interactions is further highlighted by seasonal and species-specific variations, which are indicative of the adaptive characteristics that certain plant species possess and can be utilized for the purpose of urban greening and pollution mitigation. The adverse effects of vehicular emissions must be mitigated through the implementation of urban green belts and the use of pollution-tolerant species. Nevertheless, the long-term and combined effects of pollution and climate change on flora are still not fully understood. Interdisciplinary studies are essential for the integration of the physical, chemical, and biological dimensions of pollution impacts, while emerging technologies such as remote sensing and biomarkers offer promising instruments for advancing this field. It is important to address the impact of vehicular pollution on plants in order to safeguard human health and advance sustainable urban development, as well as to preserve ecological equilibrium. In order to mitigate these effects and maximize on the potential of vegetation as a natural solution to environmental challenges, it is essential to implement targeted research and evidence-based policies.

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