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Review paper

Roadside Tree Plantations: A Review of Their Role in Pollution Control and Ecological Importance

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ABSTRACT

This paper provides a comprehensive review of roadside tree plantations, highlighting their critical function as essential green infrastructure in mitigating various forms of environmental pollution and enhancing urban ecological health. It details the intricate mechanisms by which trees contribute to air, noise, and water quality improvements, alongside their broader ecological significance in supporting biodiversity, regulating microclimates, and stabilizing soil. The review also addresses the inherent challenges in establishing and maintaining these green assets within the complex roadside environment. Furthermore, it examines the diverse methodologies employed to assess their effectiveness and identifies key research gaps. The synthesis underscores the multidisciplinary benefits of roadside tree plantations and emphasizes the imperative for strategic planning and integrated management to foster sustainable and resilient urban environments.

1. 1. Introduction

1.1 *Background: The Urban-Roadside Environment and the Need for Green Infrastructure*

The relentless pace of global urbanization has fundamentally transformed natural landscapes, leading to a significant increase in impervious surfaces, alterations in natural hydrological cycles, and a substantial rise in environmental pollution, particularly concentrated within and along urban road corridors. Road networks, while vital for connectivity and economic activity, are concurrently recognized as major anthropogenic sources contributing to a spectrum of environmental degradation, including air, noise, and water pollution. They also exacerbate habitat fragmentation and intensify the urban heat island effect, posing considerable challenges to environmental health and human well-being.

In response to these pervasive environmental pressures, roadside vegetation, encompassing a strategic integration of trees, shrubs, and grasses, is increasingly acknowledged as a crucial component of urban green infrastructure **[1, 6]**. These deliberate plantations offer a nature-based solution, possessing the capacity to transform the negative environmental impacts associated with roads into productive assets. They actively alleviate detrimental effects on local environments, contributing to a more sustainable and livable urban fabric **[11, 37]**. The conceptualization of urban green spaces, and specifically roadside trees, as "living technology" and a "key component of the urban infrastructure" **[35]** represents a profound shift in perspective. This terminology implies that trees are not merely aesthetic enhancements or discretionary "green amenities," but rather functional, essential systems within the urban fabric **[8]**. This understanding suggests that their planning, implementation, and, crucially, their long-term maintenance should be approached with the same rigorous engineering principles, financial commitment, and strategic foresight typically applied to traditional grey infrastructure, such as roads, sewage systems, and power grids. This re-evaluation necessitates a fundamental shift in how urban and transportation agencies perceive and budget for roadside vegetation, moving from a perceived discretionary expense to a critical investment with quantifiable returns in public health, environmental quality, and economic stability. Furthermore, this perspective inherently demands greater interdisciplinary collaboration from the earliest planning stages, involving a diverse array of experts including landscape architects, civil engineers, soil scientists, ecologists, botanists, entomologists, and wildlife conservationists. This reframing has the potential to unlock more substantial and sustained funding streams, foster more integrated urban design, and promote a holistic approach to urban sustainability, recognizing the multi-functional and cost-effective nature of green infrastructure in addressing complex urban challenges.

1.2 Scope and Objectives of the Review

This review paper aims to synthesize the current scientific understanding regarding the multifaceted roles of roadside tree plantations in mitigating environmental pollution and their broader ecological importance within urban and peri-urban landscapes. It will critically examine the underlying mechanisms through which these benefits are achieved, discuss the practical challenges encountered in their implementation and long-term management, and review the diverse methodologies employed to assess their effectiveness.

The specific objectives of this review are:

- To comprehensively detail the specific mechanisms by which roadside trees contribute to the mitigation of air, noise, and water pollution.
- To elaborate on the wide array of ecological services provided by roadside tree plantations, including their contributions to biodiversity support, microclimate regulation, and soil health.
- To identify and analyze common challenges and negative impacts associated with establishing and maintaining roadside trees, proposing best practices for sustainable management.
- To present and critically evaluate current methodologies and assessment techniques used for quantifying the environmental and ecological benefits of roadside trees.
- To highlight significant research gaps and propose future directions for scientific inquiry and policy development aimed at optimizing sustainable roadside tree management.

2. Materials and Methods

2.1 Literature Search and Selection Criteria

This review was meticulously conducted through a comprehensive analysis of a curated collection of research materials. The selection of these materials was based on their direct relevance to the core themes of the review: roadside tree plantations, their role in pollution control, and their ecological importance.

The guiding terms used for reviewing the provided material included: "roadside tree plantation definition objectives practices," "urban forestry roadside planting benefits," "roadside trees air pollution removal mechanisms review," "vegetation noise barrier effectiveness research," "trees stormwater runoff reduction mechanisms academic," "roadside vegetation biodiversity enhancement studies," "urban trees microclimate regulation research," "trees soil erosion control roadside academic," "urban ecosystem services roadside trees review paper," "phytoremediation roadside trees heavy metals nutrients," "challenges in urban tree planting for pollution control," "limitations of i-Tree model for roadside environments," "methods for assessing air pollution removal by trees," "acoustic measurement techniques for vegetation noise barriers," "stormwater runoff quality assessment methods urban trees," "ecological assessment methods roadside vegetation," "impact of de-icing salts on roadside vegetation and biodiversity," and "roadside vegetation invasive species spread management."

Emphasis during the selection and interpretation of information was placed on scientific articles, technical reports, and governmental guidelines to ensure the credibility, academic rigor, and practical applicability of the synthesized knowledge.

2.2 Data Extraction and Synthesis Approach

Information pertinent to the review's objectives was systematically extracted from each piece of research and categorized according to the predefined sections of the outline (e.g., air pollution mechanisms, biodiversity benefits, challenges, assessment tools).

The synthesis process involved identifying explicit statements regarding benefits, underlying mechanisms, prevailing challenges, and established methodologies. A critical analytical approach was employed to discern patterns, identify consistencies, highlight contradictions or areas of debate, and pinpoint knowledge gaps requiring further investigation. Quantitative data, such as reported decibel reductions for noise, carbon sequestration rates, or temperature reductions, were carefully noted and integrated where available to substantiate claims of effectiveness and provide empirical support. A significant aspect of the synthesis involved moving beyond surface-level information to identify deeper implications. This was achieved by systematically cross-referencing information across multiple sources, exploring potential causal relationships, inferring broader consequences, and identifying emerging themes that might not be immediately apparent from individual data points. This iterative process allowed for the construction of a comprehensive and nuanced understanding of the complex interactions between roadside trees and their environment.

3. Results and Discussion

3.1 Pollution Control by Roadside Tree Plantations

3.1.1 Air Pollution Mitigation: Mechanisms and Effectiveness

Roadside trees function as natural, living filters, playing a pivotal role in significantly improving air quality in urban and peri-urban environments by actively removing a diverse range of atmospheric pollutants. The mechanisms by which trees achieve this vital environmental service are multifaceted **[11, 12, 13]**:

Gaseous Pollutant Absorption:
Trees absorb gaseous pollutants such as carbon dioxide (CO_2), ozone (O_3), nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2) primarily through their leaf stomata—microscopic pores on leaf surfaces that facilitate gas exchange. During photosynthesis, CO_2 is converted into oxygen, which is then released back into the atmosphere, contributing to atmospheric oxygen replenishment.

Particulate Matter Interception and Deposition:
The complex, rough surfaces of tree canopies, including leaves, stems, and twigs, physically intercept and trap airborne particulate matter (PM), such as dust, ash, pollen, and smoke (including PM_{10} and $PM_{2.5}$) **[12]**. Once trapped, these particles are either washed to the ground by rainfall or fall with shed leaves, effectively removing them from the ambient air and preventing their inhalation.

Microclimate Regulation:
Trees contribute indirectly to air quality improvement by altering local microclimates. Through shading and evapotranspiration, trees reduce ambient air temperatures **[22]**. This temperature reduction is crucial because the formation and concentration of certain pollutants, notably ozone (smog), are temperature-dependent. Lowering temperatures also reduces the demand for air conditioning in buildings, thereby decreasing energy consumption and, consequently, emissions from power plants **[7]**.

The effectiveness of roadside trees in air pollution mitigation can be quantitatively substantial. A healthy, mature tree can sequester approximately 13 pounds of carbon annually, translating to about 2.6 tons per acre each year **[7]**. Projections suggest that 100 million mature trees in U.S. cities could lead to an annual energy use reduction of 30 billion kWh, saving approximately $2 billion, and a reduction of 9 million tons per year in carbon dioxide emissions from power plants **[12]**. Computer simulations indicate that trees can appreciably reduce ozone in polluted air, with pine trees in Los Angeles projected to remove about 8% of ozone from the atmosphere (under 400 meters) and decrease concentration around leaves by 49% **[15]**. A mature urban tree is estimated to intercept up to 50 pounds of particulates per year **[7]**. For instance, planting 500,000 trees in Tucson was projected to reduce airborne particulates by 6,500 tons annually **[7]**.

The efficacy of pollutant reduction is significantly influenced by the physical characteristics of the vegetation, including its height, thickness, density, and overall coverage **[15]**. Studies highlight that denser vegetation, with a leaf area density of 3.0 $m^2\ m^{-3}$ or higher, is necessary for substantial reductions in airborne particulate matter. Conversely, highly porous vegetation or scattered trees with significant gaps can, in some cases, lead to increased downwind pollutant concentrations due to altered airflow patterns that may trap pollution plumes **[15]**. This observation, where some studies report reductions while others indicate increases in pollutant levels, demonstrates that the mere presence of vegetation does not guarantee air quality improvement. The resolution of this apparent contradiction lies in the specific characteristics of the vegetation. Densely planted, thick vegetation with full ground coverage effectively reduces pollutants, while porous stands or scattered trees with gaps can worsen air quality by trapping vehicle emissions due to altered airflow dynamics **[16, 17]**. This reveals that the physical structure, including crown density, height, leaf area index, and overall barrier thickness, of the trees is as crucial as their inherent biological capacity for pollutant absorption. It is not simply about planting trees, but about implementing a scientifically informed, strategic planting design. This understanding transforms roadside tree planting from a general "green initiative" into a highly specialized "green engineering" discipline. It underscores the necessity for urban planners and landscape architects to consider micro-scale aerodynamics and pollutant dispersion patterns during the design phase. This may involve utilizing computational fluid dynamics (CFD) modeling to predict airflow and optimize tree placement and species selection for maximum air quality benefits, especially in complex urban environments with varying building densities and traffic flows.

Table 1 Key Air Pollutants Mitigated by Roadside Trees and Mechanisms

Pollutant Category	Specific Pollutants	Primary Mechanism(s) of Removal/Mitigation
Gaseous Pollutants	Carbon Dioxide (CO2)	Photosynthesis (uptake from atmosphere, release of O2)
	Ozone (O3)	Stomatal absorption; Indirectly via temperature reduction
	Nitrogen Oxides (NOx)	Stomatal absorption
	Carbon Monoxide (CO)	Stomatal absorption
	Sulfur Dioxide (SO2)	Stomatal absorption
Particulate Matter	PM10, PM2.5, Dust, Ash, Pollen, Smoke	Physical interception and trapping on leaf/bark surfaces; Subsequent wash-off by rain or deposition with leaf fall
Indirect Mitigation	Heat (Urban Heat Island Effect)	Shading, Evapotranspiration (cooling air); Reduces energy demand, thus power plant emissions

3.1.2 Noise Pollution Reduction: Principles and Influencing Factors

Roadside vegetation, particularly when designed as dense tree and shrub communities, can significantly attenuate traffic noise, contributing to a quieter urban environment **[18, 19]**. The principles governing sound attenuation by vegetation involve a combination of physical and perceptual mechanisms.

Mechanisms of Sound Attenuation:

Absorption: Leaves, twigs, and branches physically absorb sound energy. The microscopic trichomes (hairs) and stomata on leaf surfaces also contribute to noise absorption **[23]**.

Reflection/Scattering: Sound waves are reflected and scattered by the rigid structures of tree trunks, branches, and the dense, complex foliage. This scattering is identified as a primary mechanism of sound attenuation by vegetation **[24]**.

Refraction: As sound waves pass through vegetative barriers, they can bend or refract around plant structures, further contributing to attenuation.

Masking: The natural sounds produced by vegetation, such as the rustling of leaves, the swaying of branches, and the sounds of wildlife (e.g., birds, insects) attracted to the green spaces, can effectively mask or obscure unwanted noise pollution **[20]**.

Influencing Factors and Effectiveness:

Width and Density: The width of the vegetation barrier is linearly proportional to the amount of sound absorption. Densely planted trees with thick trunks and tall shrubs significantly enhance physical noise reduction effectiveness. To achieve a sound absorption of 5 dB(A) or better, a vegetation barrier width of at least 1.5 meters is recommended **[18]**.

Height: While some studies indicate no clear linear dependency on the height of the vegetation barrier for physical noise reduction **[21]**, others emphasize that physical noise reduction effectiveness is closely related to vertical canopy density. Taller crowns can also intercept wind at higher levels, reducing wind speed at ground level and potentially creating calmer acoustic conditions below.

Frequency: Vegetation barriers are more effective at attenuating higher frequency noise (above 4 kHz), showing heavy attenuation, while exhibiting virtually no attenuation for low-frequency noise (below 100 Hz) **[19]**. Most significant road traffic noise occurs in the mid-frequency range, where 4 dB(A) or above absorption rates due to vegetation barriers have been observed.

Species Type: Broadleaf trees generally demonstrate superior unit noise reduction effectiveness compared to coniferous trees, primarily due to their denser foliage, which increases overall noise absorption capacity **[19]**.

Community Composition: The most effective plant community combination for comprehensive noise reduction, encompassing both physical and psychological benefits, is a mixed composition of densely planted trees, shrubs, and ground cover.

Beyond measurable physical attenuation, vegetation significantly contributes to psychological noise reduction. This is achieved by improving visual perception, for instance, through strategic shrub crown width, height, and spacing, which can screen harsh scenery and provide pleasant forms and colors. Simultaneously, vegetation enriches auditory perception through natural masking sounds and a more harmonious sound environment, which collectively raises the auditory annoyance threshold, making perceived noise less bothersome **[19]**. This distinction between physical and psychological noise reduction is crucial. It highlights that the value of roadside trees for noise control extends beyond objective acoustic engineering metrics to the realm of public health and well-being, where the perceived quality of the environment contributes significantly to human comfort and satisfaction. This implies that urban planning and design for noise mitigation should adopt a holistic approach, integrating both objective acoustic measurements and subjective human perception studies to capture the full spectrum of benefits. This comprehensive understanding expands the justification for investing in green noise barriers, emphasizing their role in creating more livable, aesthetically pleasing, and psychologically restorative urban environments, thereby enhancing overall quality of life beyond mere pollution abatement.

3.1.3 Water Pollution Control and Stormwater Management: Mechanisms of Runoff Reduction and Pollutant Filtration

Roadside trees are integral components of green infrastructure, playing a critical role in effective stormwater management and the improvement of water quality within urban landscapes. Their contribution is achieved through a combination of physical, biological, and chemical processes **[25, 26, 27]**.

Mechanisms of Runoff Reduction:

Rainfall Interception: Tree canopies intercept a significant portion of rainfall before it reaches the ground, thereby reducing the volume and velocity of surface runoff. This interception delays the onset of runoff and allows a greater proportion of water to evaporate back into the atmosphere (evapotranspiration) or to be absorbed by the surrounding vegetation and soils **[2, 9]**. A single tree, for instance, can intercept and store over 100 gallons of water **[9]**.

Infiltration Enhancement: The extensive root systems of trees loosen and aerate compacted urban soils, which are often characterized by poor permeability. This action increases the soil's capacity to absorb water, thereby reducing surface runoff and promoting vital groundwater recharge. This process also helps prevent detrimental gully formation and soil erosion **[2]**.

Reduced Runoff Velocity: Groundcover, grasses, and other vegetation within roadside plantations provide physical resistance to water flow, effectively slowing down runoff velocities **[27]**. Slower runoff allows more time for water to infiltrate the soil and for various pollutant removal processes to occur.

Mechanisms of Pollutant Filtration and Removal:

Sedimentation: By reducing the velocity of stormwater runoff, trees and associated vegetation facilitate the gravitational settling of suspended solids and sediments, preventing their transport into waterways.

Physical Filtration: Particulate pollutants are physically strained out as stormwater passes through the porous filter media of soil, organic matter (e.g., mulch, leaf litter), or engineered soil mixes. These particles are trapped on the surface or within the pores of the filter media **[28]**.

Adsorption: Soluble pollutants, including various heavy metals, excess nutrients (e.g., organic Nitrogen, orthophosphate ion), and organic compounds, are removed through adsorption. This process involves ions and molecules attaching to binding sites on the surfaces of filter media particles, particularly in soils with high organic matter content, clay content, or high cation exchange capacity **[27]**.

Phytoremediation: Trees and associated plants actively participate in the removal, detoxification, or immobilization of contaminants from both soil and water **[29, 30]**. Specific phytoremediation techniques include **[31, 32]**:

- **Phytoextraction:** Metal contaminants are absorbed by plant roots and then translocated and accumulated in the harvestable upper portions of the plant (stems and leaves). Hyperaccumulator plant species are often utilized for their enhanced capacity to extract contaminants.
- **Rhizofiltration:** This technique involves filtering water through a dense mass of plant roots, which absorb or adsorb toxic substances or excess nutrients from the water.
- **Phytostabilization:** This process reduces the mobility and bioavailability of heavy metals in contaminated soil by decreasing wind-blown dust, minimizing soil erosion, and reducing contaminant solubility, thereby preventing their entry into the food chain.
- **Phytodegradation:** Plants absorb and break down organic chemical pollutants in contaminated soil and groundwater through their metabolic processes.
- **Phytovolatilization:** Contaminants are taken up by plants from the soil and subsequently released into the atmosphere in a volatile form through transpiration.

Plant Uptake and Microbial Degradation: Growing plants directly take up nutrients and metals from the soil and incorporate them into their biomass during their growth cycle **[27]**. Furthermore, the diverse microbial communities residing in the rhizosphere (the soil zone immediately surrounding plant roots) actively degrade or transform a wide range of organic and inorganic compounds, including hydrocarbons, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), and various metals **[27]**.

The detailed mechanisms of water pollution control and stormwater management reveal that trees contribute through a complex, multi-layered cascade of natural processes. This includes physical processes like canopy interception, enhanced soil infiltration, and sedimentation, combined with sophisticated biological and chemical processes such as adsorption, direct plant uptake, and various forms of phytoremediation. This comprehensive functionality positions roadside trees not merely as passive green elements but as active, integrated "natural water treatment systems." This holistic functionality suggests that strategically integrating trees into urban water management plans can significantly reduce the reliance on and burden on traditional grey infrastructure, such as pipes and treatment plants, leading to substantial cost savings in construction and operation. It also enhances urban resilience to flooding and climate change impacts. Furthermore, it highlights the critical importance of maintaining healthy soil conditions, as the soil matrix and its associated microbial communities are integral to these filtration and degradation processes.

3.2 Ecological Importance of Roadside Tree Plantations

3.2.1 Biodiversity Enhancement and Habitat Provision

Roadside trees and their associated vegetation actively create and support local ecosystems, providing crucial habitat and food resources for a diverse array of flora and fauna, including various bird species, small animals, and, notably, a wide range of pollinators **[10]**.

Large, mature trees are considered "keystone structures" within urban landscapes due to their disproportionately significant contribution to supporting critical biodiversity. They facilitate the retention of moisture and key nutrients in the soil, promoting soil stability and supporting a vast array of microbial and invertebrate life. These mature trees function as biodiversity "hotspots," hosting many familiar species and supporting complex food webs. They also create suitable mini-climates that allow other plant species, otherwise absent from urban areas, to thrive.

Roadside corridors possess the potential to serve as vital habitat corridors, effectively linking fragmented patches of natural or semi-natural habitat **[4, 5]**. This connectivity is particularly beneficial for the dispersal and movement of pollinators, allowing them to access diverse foraging and nesting sites **[34]**. High-quality roadside habitat, when well-managed, has been shown to potentially reduce pollinator road mortality by encouraging insects to remain within the roadside verge rather than attempting to cross busy roadways.

However, the role of roadsides as ecological assets is not without complexities. While roadside vegetation is presented as enhancing biodiversity and providing habitat, particularly for pollinators, and acting as habitat corridors **[10]**, other evidence introduces a critical caveat: roadsides can also act as "ecological traps" or contribute to habitat fragmentation **[33]**. Pollinators, for instance, might be attracted to abundant floral resources along roadsides but then face higher mortality rates due to vehicular traffic, exposure to pollutants, or the impacts of maintenance practices like mowing and herbicide application **[33]**. One study explicitly states that "dispersing pollinators may incorrectly assess vegetated roadsides as good habitat, but the rates of survival and reproduction may, in fact, be lower there than in other habitats, resulting in a negative effect" **[33]**. This contradiction highlights that the ecological benefits of roadside plantations are not inherent or guaranteed by mere presence; they are contingent upon informed, adaptive, and sensitive management practices. Simply planting trees is insufficient; the quality and management of the roadside habitat are paramount. Practices such as adjusting mowing frequency and timing, reducing and targeting herbicide use, and selecting native, pollinator-friendly species become critical to ensure the roadside functions as a true habitat corridor and not a mortality sink. This underscores the necessity for a nuanced approach to roadside ecological management. It demands that transportation agencies and urban planners move beyond generic greening efforts to implement best management practices that actively mitigate risks and maximize genuine ecological value, potentially requiring long-term monitoring of pollinator populations and their health within these dynamic environments.

3.2.2 Microclimate Regulation and Urban Heat Island Effect Mitigation

Trees exert a significant influence on local climate conditions, playing a crucial role in regulating microclimates and contributing to cooler, more comfortable urban environments **[22]**. The mechanisms by which trees modify microclimates are well-established:

Shade Provision: Tree canopies directly reduce the amount of solar radiation reaching the ground and impervious surfaces, thereby lowering surface temperatures and providing essential shade. This shading effect can significantly reduce air conditioning needs in adjacent buildings, potentially by up to 30 percent **[7]**. Deciduous trees, in particular, offer strategic benefits by providing shade in hotter months and allowing sunlight penetration in colder months after leaf fall.

Evapotranspiration: Through the process of evapotranspiration, trees release water vapor into the atmosphere. This natural cooling mechanism cools the surrounding air and increases humidity in dry climates. This process is vital in moderating temperature extremes within urban areas **[35]**.

Wind Speed Reduction: Tree canopies and their structural density can reduce wind speed at ground level. This reduction in wind can be beneficial in mitigating heat loss during colder months or reducing heat gain during warmer periods, depending on the season and prevailing wind patterns.

The collective effect of transpiring trees is highly effective in mitigating Urban Heat Islands (UHIs), which are characterized by cities being 3 to 10 degrees Fahrenheit warmer than surrounding rural areas due to thermal energy storage in concrete, steel, and asphalt. Studies indicate that trees with expansive crowns and a high Leaf Area Index (LAI > 4) can reduce ambient temperatures by 1.5–5°C **[22]**. The reduction in air temperatures achieved by trees also indirectly contributes to improved air quality by lowering the emission rates of temperature-dependent pollutants and reducing the formation of ground-level ozone (smog). For example, a 1°C increase in temperature can lead to a 1% increase in smoggy days **[12]**. This demonstrates a causal, synergistic link between microclimate regulation and air quality improvement. The climate benefits of trees extend beyond carbon sequestration and energy savings to immediate, tangible improvements in urban air quality and, consequently, public health. This synergy makes roadside tree planting an even more powerful and cost-effective tool for integrated urban environmental management. It allows cities to address multiple pressing issues—heat stress, energy consumption, and air pollution—simultaneously with a single green infrastructure intervention, thereby enhancing overall urban resilience to climate change and improving livability.

3.2.3 Soil Stabilization and Health Improvement

Roadside trees are fundamental to maintaining soil integrity, preventing erosion, and enhancing overall soil health within the challenging roadside environment. Their presence contributes to the physical and biological well-being of the soil through several mechanisms:

Erosion Control: The extensive root systems of trees firmly hold soil in place, significantly reducing soil erosion and preventing the formation of gullies, particularly on slopes and along streambanks **[2]**. Additionally, groundcover grasses and other vegetation within roadside plantations help to reduce runoff velocity and trap sediments, further mitigating erosion.

Increased Soil Permeability and Infiltration: Tree roots physically loosen and aerate compacted urban soils, which are often characterized by poor permeability. This action increases the soil's capacity to absorb water, thereby reducing surface runoff and promoting vital groundwater recharge **[2]**.

Organic Matter Contribution: The shedding of dead leaves, twigs, and other organic matter from trees contributes significantly to the formation of organic soil and enriches the soil's composition. This organic matter aids in enhanced water infiltration and improves the soil's water retention capabilities **[2]**. The application of mulch around newly planted trees also enriches the soil, helps retain moisture, and suppresses weed germination, further improving soil health **[43, 44]**.

Pollutant Filtration within Soil: Trees and the soil matrix around them function as natural filters, capturing and breaking down various pollutants. The soil acts as a sink for contaminants, with studies showing a positive correlation between vehicular density and levels of potentially toxic elements (PTEs) in the soil **[42]**. The soil's ability to retain heavy metals is enhanced by higher plant biomass and organic matter content **[42]**. This filtration is crucial in preventing the transport of chemicals to streams.

4. Challenges and Considerations in Roadside Tree Plantation

Despite the numerous benefits, the establishment and long-term success of roadside tree plantations face significant challenges inherent to the urban environment and the specific demands of roadside conditions. These obstacles necessitate careful planning and adaptive management strategies **[39]**.

4.1 Environmental and Site-Specific Challenges

Roadside environments present harsh growing conditions that severely limit tree survival and health. These include:

Limited Soil and Space: Trees are often planted in confined spaces with insufficient soil volume, surrounded by impervious surfaces like pavement and concrete. This leads to soil compaction, poor permeability, and limited water availability, contributing to high tree mortality rates and poor health **[39]**.

De-icing Salts: The common use of de-icing salts (primarily sodium chloride) on roads and pavements during winter is highly detrimental to roadside vegetation **[40, 41]**. Salts can be absorbed by plant roots, causing dehydration, and salt spray can burn foliage, particularly on evergreens. Sodium also causes clay particles in soil to expand, increasing compaction and reducing water infiltration, making root growth difficult.

Extreme Temperatures and Drought: Urban heat island effects exacerbate high temperatures, leading to heat stress, reduced photosynthesis, and increased evapotranspiration rates, often resulting in leaf die-off and defoliation **[39]**. Extended dry spells and droughts further stress trees, especially newly planted seedlings that require consistent moisture for establishment.

Pests and Diseases: Roadside trees are susceptible to various environmental threats, including insect borers, canker-causing fungi, and other pests and pathogens that can severely damage or kill trees within a few years **[39]**.

Pollutant Accumulation in Soil: Beyond direct vehicular emissions, urban water runoff leads to the deposition of heavy metal pollutants into street tree soils, which can progressively alter soil pH and negatively affect plant physiological and reproductive characteristics, including germination and seedling development **[42]**.

4.2 Management and Maintenance Issues

Effective maintenance is paramount for the establishment and long-term health of roadside plantations, yet it often presents significant challenges **[43]**:

Lack of Planning and Resources: Many tree planting initiatives focus on initial planting numbers rather than long-term survival and thriving. Inadequate planning and insufficient allocation of resources for ongoing maintenance are primary reasons for seedling mortality **[39]**.

Physical Damage: Roadside trees are highly vulnerable to physical damage from various sources, including construction activities that damage roots, poor pruning practices, and direct vandalism. Vehicles, lawnmowers, and string trimmers can cause wounds and injuries to trunks, impairing the vascular transport of water and nutrients **[39]**.

Competition and Animal Damage: Nursery seedlings often die due to competition with other vegetation, high surface temperatures, high evapotranspiration rates, lack of soil moisture, and damage from animals, necessitating protective measures like fencing **[39]**.

Pruning Challenges: While essential for developing strong structural branches and maintaining sightlines, improper or insufficient pruning can lead to uncontrolled growth, causing problems for vehicles and reducing sight distance **[38]**.

4.3 Safety and Infrastructure Conflicts

The proximity of trees to roads and urban infrastructure creates specific safety and operational challenges:

Reduced Sight Distance and Obstruction: Uncontrolled growth of trees and shrubs can reduce sight distance for drivers, obstruct traffic signs, and impair overall visibility, particularly on curves **[38]**.

Vehicle and Personal Injury Risk: Overhanging or low-growing branches can cause damage to vehicles or pose risks of personal injury to pedestrians and cyclists **[38]**.

Utility Conflicts: Trees can interfere with overhead power lines, necessitating specific pollarding strategies, and their root systems can disrupt underground utilities such as water service lines. Before digging, it is crucial to call utility notification centers to mark underground lines **[36]**.

Debris on Roads: Roadside vegetation can contribute to debris on roads, potentially creating hazards **[38]**.

4.4 Invasive Species and Herbicide Use

The management of roadside vegetation often involves confronting invasive species, which can outcompete native plants and reduce ecological value:

Spread of Invasive Plants: Invasive plants, such as stinkwort and scotch broom, thrive along highways, competing with local vegetation **[45]**. Mowing or weed trimming can inadvertently exacerbate the problem by spreading invasive seeds.

Herbicide Reliance and Protocols: To control tenacious invasive weeds, herbicides are often used. However, their application requires strict protocols, including maintaining buffer zones near waterways, private driveways, and mailboxes, and avoiding spraying during high winds to prevent drift **[38]**. The choice of herbicide (pre-emergent vs. post-emergent) and its environmental impact must be carefully considered.

The challenges inherent to roadside tree plantations are not isolated but are interconnected, often exacerbating one another. For instance, limited soil volume and compaction not only hinder tree growth but also make trees more susceptible to drought, pests, and diseases. Similarly, the use of de-icing salts can directly harm trees and also contribute to soil degradation, further compromising their resilience. This interconnectedness underscores that successful roadside tree programs require a holistic, integrated management approach that addresses multiple factors simultaneously, moving beyond single-issue solutions. This necessitates comprehensive planning that considers site characteristics, species selection, long-term maintenance needs, and potential conflicts with infrastructure and safety from the outset. Effective roadside tree management requires a paradigm shift towards proactive, integrated strategies that recognize the complex interplay of environmental stressors and operational demands.

5. Assessment Methodologies and Monitoring

Accurately quantifying the benefits of roadside tree plantations is essential for justifying investments, optimizing management strategies, and informing policy decisions. Various methodologies and assessment techniques are employed across different environmental parameters.

5.1 Air Pollution Removal Assessment

Assessing air pollution removal by urban trees involves a combination of modeling and direct measurement approaches:

i-Tree Eco Model: The i-Tree Eco model, developed by the U.S. Forest Service, is a widely used software tool that quantifies the structure and environmental effects of urban forests, including air pollution removal **[14, 46]**. It estimates the hourly dry deposition of pollutants (O3, SO2, NO2, CO, PM10, PM2.5) based on tree, shrub, and grass cover data, hourly weather data, and pollution-concentration monitoring data **[47]**.

Calculation: Pollution removal (flux) is calculated using deposition velocity (Vd) and pollutant concentration (C), where Vd is derived from aerodynamic, quasi-laminar boundary layer, and canopy resistances. Canopy resistance for gaseous pollutants is based on stomatal, mesophyll, and cuticular resistances, influenced by factors like photosynthetic active radiation, air temperature, and wind speed.

Scaling: Hourly pollutant flux per unit tree canopy is scaled up by total tree-canopy coverage to estimate total hourly pollutant removal across a study area. The model also estimates individual tree effects based on leaf area and calculates percentage air quality improvement using mixing height data.

Economic Valuation: Health benefits and their economic value are estimated using models like the U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP), translating pollution removal into healthcare savings and productivity gains **[14]**.

Advantages: i-Tree Eco produces deposition velocities consistent with field data and is the only known program to couple tree pollution removal with health benefit estimation **[14]**.

Limitations and Uncertainties: The model often relies on limited spatial resolution of concentration data (e.g., one local monitor). It does not fully account for local-scale interactions with wind, potential pollution formation from volatile organic compounds (VOCs) emitted by some trees, or health impacts from tree pollen. It also assumes ample soil moisture, potentially overestimating removal during droughts, and estimates for PM10 and CO removal are considered rudimentary. i-Tree Landscape, another tool, may underestimate tree cover **[47]**.

Direct Measurement and Passive Samplers: Field measurements using low-cost air quality sensors (PM2.5, NO2, CO) and air pumps can interrogate air quality within tree canopies compared to ambient air **[48]**. Passive samplers are also used to measure gaseous pollutants and assess pollutant exposure, enabling cities to analyze air pollutant trends **[49]**.

Biomonitoring using Tree Bark: The analysis of chemical elements in tree barks offers an alternative procedure to assess the spatial heterogeneity of traffic-related air pollution. Species with rough and highly porous bark, like Tipuana tipu, are particularly appropriate for biomonitoring, as they can effectively record airborne element concentrations **[50]**.

Computational Fluid Dynamics (CFD) Modeling: CFD models are increasingly used to simulate the dispersion of pollutants in urban environments, allowing for detailed analysis of airflow, turbulent eddies, and the impact of vegetation density on pollutant levels **[16, 17]**. These models can identify recirculation zones in street canyons and pinpoint streets contributing most significantly to pollution.

5.2 Noise Reduction Evaluation

Evaluating the noise reduction effectiveness of vegetation barriers involves both acoustic measurements and consideration of various parameters:

Acoustic Measurements: Field measurements typically involve recording A-weighted continuous noise levels with and without vegetation barriers to quantify decibel (dB) attenuation **[18]**. Laboratory tests often use impedance tubes or reverberation chambers to analyze the acoustic absorption properties of plant components. In-situ measurements of noise reflection can also be performed to estimate sound absorption coefficients **[23]**.

Parameters Considered: Key parameters influencing noise attenuation include the width, density, and height of the vegetation barrier **[19]**. Broadleaf trees generally outperform coniferous trees due to denser foliage. The effectiveness varies with frequency, with higher frequency noise (above 4 kHz) being heavily attenuated, while low-frequency noise (below 100 Hz) shows little attenuation.

Psychological Assessment: Beyond physical measurements, studies assess psychological noise reduction through surveys and virtual reality, evaluating visual perception (color, space, layering, atmosphere, attractiveness) and auditory perception (quietness, harmony, liveliness, richness, pleasantness, annoyance) **[19]**. This acknowledges that perceived quietness is not solely a function of decibel reduction.

5.3 Stormwater Management and Water Quality Assessment

Assessing stormwater runoff volume and quality, and pollutant removal by urban trees, involves various methods, though some areas require further research:

Canopy Interception Loss: This is measured indirectly by subtracting stemflow (water running down the trunk) and throughfall (water passing through the canopy or dripping off) from gross precipitation **[2]**. This method quantifies the volume of water retained by the canopy and subsequently evaporated.

Infiltration and Runoff Volume: The effectiveness of green infrastructure, including trees, at reducing stormwater runoff volume is assessed through various studies, often focusing on on-site retention, infiltration, and enhanced evapotranspiration. Tensiometers can be used to monitor water exfiltration from storage galleries and soil moisture patterns in the vadose zone **[52]**.

Pollutant Concentration and Load: Pollutant concentrations in stormwater runoff are measured through various sampling techniques, including flow-weighted discrete or composite samples, and time-weighted discrete samples **[53]**. Models like the Simple Method are used to estimate pollutant loading based on runoff volume and pollutant concentration.

Pollutant Removal Mechanisms: While canopy interception reduces runoff volume and associated pollutant washout, and trees in green infrastructure can reduce nutrient concentrations **[27]**, specific assessment methods for quantifying pollutant removal by urban trees (e.g., heavy metals, nutrients, sediments) are less detailed in some literature. Phytoremediation processes (phytoextraction, rhizofiltration, phytostabilization) are recognized for their role in removing or immobilizing contaminants, but their precise quantification in roadside contexts often requires specialized studies.

Modeling Limitations: Existing models, such as i-Tree, that estimate the impacts of trees on stormwater runoff at city or watershed scales, contain simplifying assumptions that require further field validation and calibration **[47]**. There is a recognized need for more robust model parameterization that considers species-specific interception and transpiration rates, local soil conditions, topography, and precipitation patterns.

5.4 Ecological Assessment

Ecological assessment of roadside vegetation encompasses biodiversity metrics, microclimate monitoring, and soil health analysis:

Biodiversity Metrics: Assessments often involve evaluating roadside conditions relevant to pollinators, including vegetation type, remnant habitats, invasive weeds, adjacent land use, and the width and topography of the right-of-way **[54]**. Quantitative methods include assessing vegetation cover, native species richness, and the proportion of native to exotic species. The "Habitat Hectares" approach compares existing vegetation features to benchmarks of undisturbed native vegetation to score vegetation quality **[55]**.

Microclimate Monitoring: Microclimatic parameters such as air temperature, relative humidity, wind speed, and solar radiation intensity are measured, often using a quasi-regular grid of sensors **[56]**. Remote sensing techniques, including satellite data and UAVs, are increasingly used to identify shifts in vegetation cover and assess microclimatic changes, with the Normalized Difference Vegetation Index (NDVI) being widely used for vegetation vigor and cover **[57, 58]**.

Soil Health Analysis: Soil properties such as temperature, moisture, and electrical conductivity are measured, often in conjunction with vegetation surveys **[59]**. Advanced soil health monitoring technologies, including IoT sensors and AI-driven analytics, track soil moisture, nutrients, and biological activity in real-time, informing practices that maintain long-term soil fertility and carbon sequestration. Samples of vegetation and soils are collected and stored for subsequent analysis of plant traits or genomic data.

The methodologies for assessing the environmental and ecological benefits of roadside trees are evolving from simple measurements to complex predictive models and integrated planning tools. This progression emphasizes a shift towards data-driven, proactive urban planning that integrates environmental benefits directly into infrastructure design. The use of advanced sensors, remote sensing, and computational models allows for more precise quantification of benefits and a better understanding of the complex interactions within urban ecosystems. This evolution supports the notion of trees as essential urban infrastructure, where their performance can be monitored, evaluated, and optimized with increasing sophistication, thereby informing more effective and sustainable urban development strategies.

6. Conclusion

Roadside tree plantations represent a critical and multifaceted component of urban green infrastructure, offering substantial benefits for pollution control and ecological enhancement within increasingly urbanized landscapes. This review has demonstrated that trees are not merely aesthetic additions but active agents in mitigating air, noise, and water pollution through a complex interplay of physical, chemical, and biological mechanisms. They absorb gaseous pollutants, intercept particulate matter, attenuate sound through absorption and scattering, and manage stormwater runoff through interception, infiltration, and various phytoremediation processes. Beyond pollution abatement, roadside trees play a vital ecological role by enhancing biodiversity, providing crucial habitat, regulating local microclimates, and improving soil health and stability.

The effectiveness of these benefits is profoundly influenced by strategic planning, appropriate species selection, and diligent, long-term maintenance. The understanding of trees as "living technology" underscores the necessity of approaching their management with the same rigor and investment as traditional grey infrastructure. However, the urban roadside environment presents significant challenges, including limited growing space, soil compaction, de-icing salt impacts, and the risks of physical damage and invasive species. These challenges highlight that the ecological benefits, particularly for biodiversity, are contingent upon informed and adaptive management practices that transform potential "ecological traps" into genuine habitat corridors.
Current assessment methodologies, ranging from advanced modeling tools like i-Tree Eco and Computational Fluid Dynamics to direct field measurements and biomonitoring techniques, are continuously improving. These tools enable a more precise quantification of benefits and provide a data-driven foundation for urban planning. The evolution of these assessment methods reflects a growing recognition of the need for integrated approaches that consider both the physical and psychological impacts of green infrastructure.

Future research should focus on addressing existing knowledge gaps, particularly in long-term monitoring of tree performance in diverse roadside conditions, conducting comprehensive cost-benefit analyses that encompass the full spectrum of ecosystem services, and understanding the specific impacts of climate change on tree health and efficacy. Further studies are also needed to refine local-scale modeling for more accurate predictions of pollutant dispersion and to develop robust methodologies for quantifying the removal of specific water pollutants by roadside trees. Optimizing species selection for resilience to urban stressors and maximizing multiple co-benefits should remain a priority. By continuing to invest in research, strategic planning, and integrated management, roadside tree plantations can be fully leveraged as indispensable assets for creating healthier, more resilient, and sustainable urban environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review.

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