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Nature-Based Solutions for Air Pollution Control: Role of Plants, Urban Forests, and Green Technologies

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Abstract

Urban air pollution poses a significant public health crisis, exacerbated by heterogeneous urban landscapes and diverse localized emission sources. Nature-Based Solutions (NbS), including urban forestry, green infrastructure, and engineered bio-systems, offer a sustainable, multi-functional alternative to conventional grey infrastructure for air quality management. This review examines the mechanistic foundations of pollutant removal by vegetation—dry deposition for particulate matter (PM) and stomatal uptake for gaseous pollutants—while highlighting synergistic co-benefits such as urban heat island mitigation and improved pollutant dispersion. Quantitative evidence demonstrates substantial localized and city-scale reductions in PM (up to 44%) and gaseous pollutants (13.9–36.2%). However, efficacy is context-dependent, requiring optimized design (e.g., tall, dense roadside barriers), strategic species selection to minimize biogenic volatile organic compound (BVOC) emissions, and advanced modeling to account for airflow dynamics and trade-offs. Engineered NbS, such as biofilters and constructed wetlands, further enhance targeted mitigation. Scaling NbS demands addressing governance gaps, equity concerns, standardized assessment, and economic valuation of public health benefits. Integrated, ecologically informed implementation of NbS represents a cost-effective pathway to resilient, healthier cities.

Keywords: Nature-Based Solutions (NbS), Urban air quality, Particulate matter (PM), Gaseous pollutants, Dry deposition, Stomatal uptake, Biogenic volatile organic compounds (BVOCs), Green infrastructure, Urban heat island (UHI), Species selection, Biofiltration, Constructed wetlands, Co-benefits, Policy integration, equity

1. Introduction

The escalating concentration of the global population in urban centers has amplified environmental challenges, rendering air pollution a major public health crisis. The World Health Organization (WHO) identifies air pollution as one of the leading environmental risks threatening human health and quality of life in cities (Gawrońska & Bakera, 2015). The complexity of assessing and mitigating urban air pollution stems from two primary factors: the intrinsic heterogeneity of the urban landscape and the superposition of multiple, localized pollution sources. These sources include highly variable contributions from road traffic emissions, domestic house heating (such as wood-burning fireplaces), and maritime activities (e.g., ships docked in harbors) (Menon et al., 2021). Accurate monitoring is often difficult because existing approaches frequently fail to provide the necessary spatial details and capture peak concentrations, particularly at distances removed from official monitoring stations (Theophilo et al., 2021). This critical requirement for advanced, localized, and multi-functional solutions motivates the search for alternatives to conventional grey infrastructure.

Nature-Based Solutions (NbS) have emerged as a sustainable and systemic strategy for addressing complex urban challenges, including pollution and climate resilience. The European Commission defines NbS as "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" . NbS are thus sustainable options designed to mitigate the harmful effects of climate change and pollution, thereby improving the health and well-being of city residents while benefiting biodiversity in a resource-efficient manner (European Commission, 2015). Crucially, NbS functions as a broad umbrella concept, integrating disparate but related applications, including urban forestry, the implementation of green and blue infrastructure (GBI), and various forms of urban agriculture and ecological restoration (McPhearson et al., 2025). This conceptual framework allows for the comprehensive assessment and planning of natural systems across various scales, from small-scale green facades to large urban forest expansions. The intrinsic value proposition of NbS is rooted in their ability to deliver a wide array of co-benefits that conventional engineering approaches typically cannot match. NbS provides more than passive filtration; they offer systemic urban resilience. This superiority stems from the holistic suite of non-rivalrous ecosystem services they generate. These services include the reduction of energy costs and health costs, as well as the conservation of biodiversity (Choi et al., 2025).

NbS are particularly critical for co-mitigating coupled urban challenges, most notably air pollution and the urban heat island (UHI) effect (European Commission, 2015; Ecology and Society, 2023). Vegetation contributes to a significant decrease in Land Surface Temperature (LST) through shading and the process of evapotranspiration (Chowdhury, 2024a). This reduction in urban temperature positively influences the dispersion and concentration of air pollutants, creating a synergistic effect that enhances overall air quality (Theophilo et al., 2021). The environmental benefit is therefore not limited to direct pollutant removal but includes the systemic modification of the urban microclimate. This integrated functionality necessitates a planning framework that assesses these co-benefits comprehensively, moving NbS into the urban planning agenda as a strategic, multi-functional asset (Menon et al., 2021).

Figure 1.1 Dimensions of Nature-Based Solutions in Urban Areas: Strategic Adaptation, Spatial Planning, Soft Engineering, and Performance Benefits

2. Mechanistic Foundations of Air Pollutant Removal by Vegetation

The efficacy of plants, urban forests, and green technologies in air pollution control is founded upon distinct physical and physiological mechanisms specific to the pollutant type.

2.1. Dry Deposition Processes for Particulate Matter (PM) Capture

Vegetation mitigates Particulate Matter (PM) pollution by trapping airborne particles on leaf surfaces, a process predominantly governed by dry deposition mechanisms (Rao et al., 2025). This is fundamentally a physical process influenced by the interaction of airflow, particle characteristics, and leaf surface properties.

Deposition efficiency is highly complex and dynamic, influenced by characteristics of the particles themselves such as morphology and size (Wang et al., 2020). and species-specific leaf characteristics. Key determinants on the plant side include leaf area, leaf morphology, the thickness of wax layers, and the density of trichomes (hairs) (Theophilo et al., 2021). Beyond simple interception, PM removal mechanisms also involve impaction, and chemical coagulation resulting from Brownian motion and van der Waals forces (Oral et al., 2020).

Analysis of deposited matter reveals a critical distinction between ambient air quality and localized removal. Research comparing leaf-deposited PM (LDPM) with near-filter ambient PM (NFPM) demonstrates that LDPM is chemically different from the surrounding air particles. LDPM often exhibits a greater prevalence of components associated with the Earth's crust, Heavy Metals (HMs), and combustion-related elements (LEV), compared to NFPM, which may be richer in Organic Carbon (OC) and Potassium (K) (PMCID 11145416, 2024). This chemical differentiation confirms that plant selection can be pollution-source specific. The realization that chemical composition of LDPM is dictated by specific leaf surface roughness and chemistry confirms that targeted selection strategies are necessary, moving beyond generic planting lists. Optimizing NbS design requires fundamental laboratory studies to assess actual performance under diverse weather conditions and to select species based on the dominant local contaminant fractions (Rao et al., 2025).

2.2. Gaseous Uptake: Stomatal Physiology and Gas Exchange Dynamics

Gaseous pollutants, including Sulfur Dioxide (SO2) and Ozone (O3), are removed from the atmosphere primarily through physiological processes involving gas exchange. Pollutants like

SO2 enter the leaves mainly through the stomata, which are specialized physiological structures . Stomata are indispensable for maintaining overall plant physiological and ecological functions (Dumitru et al., 2020). However, the capacity of plants to absorb gaseous pollutants via stomata is compromised by the pollutants themselves, generating a pollution-stomatal feedback loop. Exposure to air pollutants and oxidative stresses can markedly affect the Calcium (Ca2+) homeostasis of guard cells, which are responsible for regulating stomatal movement . Furthermore, heavy metal pollution can impact the structure and function of stomata, leading to changes in plant physiology and potentially limiting the plant's capacity for gaseous uptake (Pereira et al., 2021). This negative feedback loop suggests that in severely polluted urban environments, the actual physiological removal rate may be lower than theoretical maximums, demanding careful monitoring of plant health and adaptation mechanisms to sustain efficacy (Oral et l. 2020).

Table 1 synthesizes the distinct removal pathways, demonstrating that effective NbS design must simultaneously consider physical parameters for PM capture and physiological resilience for gaseous uptake.

Table 1.1 Pollutant Removal Mechanisms in Urban Vegetation

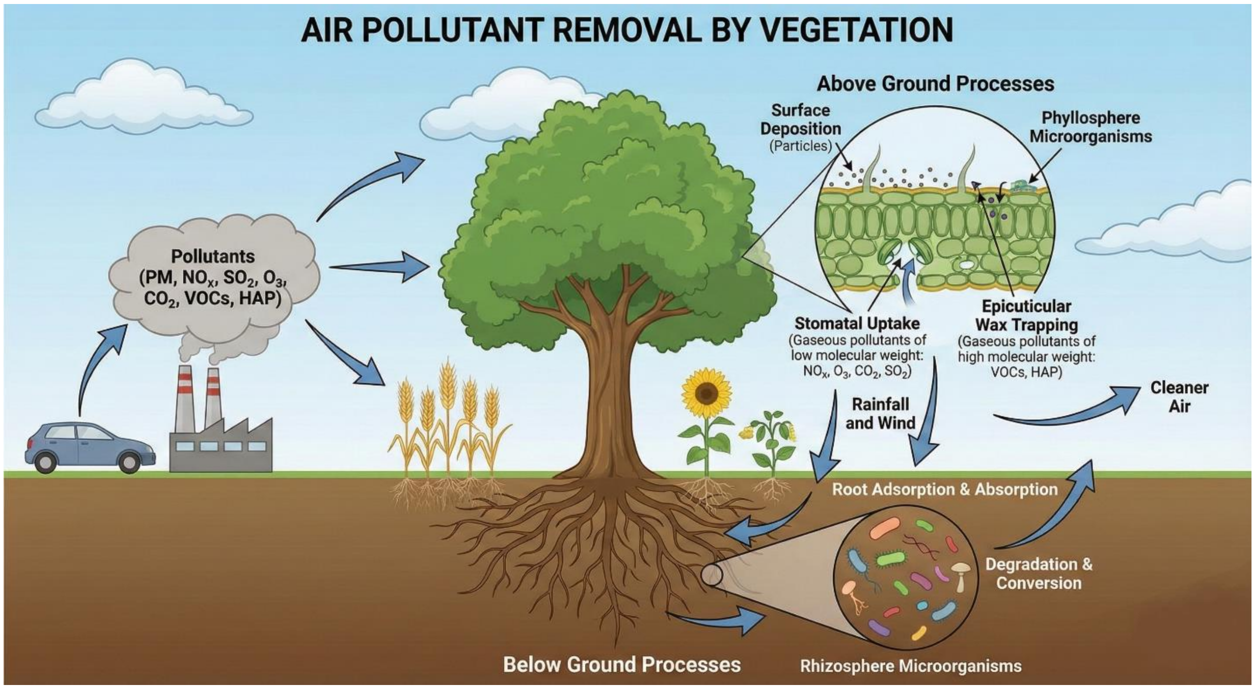
Pollutant Type	**Primary Mechanism**	**Plant Structure Involved**	**Key Influencing Factors**
Particulate Matter (PM)	Dry Deposition (Interception, Impaction, Coagulation)	Leaf Surface (Cuticle, Trichomes, Wax Layers)	Particle size and morphology, Leaf roughness, Airflow velocity (Wang et al., 2020; Philosophical Transactions of the Royal Society A, 2019)
Gaseous Pollutants (SO2, O3)	Stomatal Uptake	Stomata, Mesophyll Cells	Stomatal aperture, Internal resistance, Pollution-induced oxidative stress
Volatile Organic Compounds (VOCs)	Sorption and Metabolism/Degradation	Rhizosphere, Biofilter Medium, Microbial Population	Medium composition, Moisture content, Microbial activity (Biofiltration) (Kolekar et al., 2019;

2.3. Quantitative Metrics: Deposition Velocity (Vd) and its Limitations

To quantify the efficiency of vegetation in removing air pollutants, the rate of pollutant loss to a surface is often parameterized using the deposition velocity (Vd). This metric expresses the pollutant flux density (mass deposited per area per time) divided by the pollutant concentration in the core atmospheric region (Oral et al., 2020).

While the Vd concept has been successfully applied in some contexts, its utility for characterizing pollutant-surface interactions in complex urban environments faces limitations. The metric relies on the presumption of uniform mixing throughout the core region and assumes that deposition processes can be adequately represented as a first-order loss (Rao et al., 2025). In reality, in complex urban settings, the assumption of uniform mixing frequently fails, and deposition may vary strongly with position. Furthermore, transport rates through the boundary layer depend critically on near-surface air flow conditions, making Vd an imperfect parameter for assessing vegetative surfaces under heterogeneous urban airflow patterns (Mashanye et al., 2025).

2.1 Mechanisms of Air Pollutant Removal by Urban Vegetation: Above-Ground and Below-Ground Processes



3. Quantitative Assessment of Urban Forest and Vegetation Efficacy

The transition from understanding leaf-level mechanisms to evaluating system-scale efficacy requires quantitative assessment and atmospheric modeling to account for the dynamic interactions between vegetation structure and urban airflow.

3.1. Synthesis of Quantified Pollutant Removal Rates

Meta-analysis synthesizing global field-measurement studies provides compelling evidence of urban vegetation's quantitative effectiveness. Overall, urban vegetation is demonstrably capable of mitigating the growth of air pollutant concentrations. Synthesis results show concentration reduction rates ranging from 16.5% to 26.7% for Particulate Matter (PM), and between 13.9% and 36.2% for key gaseous pollutants, including nitrogen oxides (NOx), sulfur dioxide (SO2), and ozone (O3) (Xian et al., 2022).

At a localized scale, the impact can be highly significant. For instance, the installation of dense green screens covered in climbing vegetation near pollution sources has shown remarkable localized improvements. One case study involving a green screen installed surrounding a schoolground fence found that the presence of the screen decreased PM concentrations by up to 44% in the school playground when the wind blew from the road toward the school grounds, indicating a substantial improvement in local air quality (NatureScot, 2023).

3.2. Airflow Dynamics, Dispersion Effects, and Microclimate

The overall impact of green infrastructure (GI) on urban air quality is highly context-dependent (. The effectiveness of urban vegetation extends beyond direct removal mechanisms (uptake and deposition) to include the modification of the urban atmosphere through dispersion and microclimate regulation. Modeling studies have suggested that GI mitigation efficacy is generally dominated by dry deposition at the city-scale but is primarily driven by dispersion effects along roads, highlighting the dual functional role of NbS (Theophilo et al., 2021).

A positive feedback mechanism links NbS, air quality, and climate regulation. Vegetation significantly decreases Land Surface Temperature (LST) via evapotranspiration and shading (Bil, 2024). This LST reduction positively influences the dispersion and concentration of air pollutant. High temperatures can accelerate chemical reactions that form secondary pollutants and increase Biogenic Volatile Organic Compound (BVOC) emissions (discussed in Section 4). By reducing LST, NbS slow these negative processes while simultaneously improving atmospheric dispersion (Chowdhury et al., 2025). This synergistic relationship demonstrates that NbS targeting urban heat island mitigation are intrinsically coupled with air quality improvement, yielding a total benefit greater than the sum of deposition and uptake alone (Rao et al., 2025).

Accurate assessment of these effects demands advanced modeling. To account for the intrinsic urban landscape heterogeneity and the complex interplay of turbulent air flow, an integrated approach utilizing very high-resolution hydrodynamical models is essential. Models like the Parallelized Large-Eddy Simulation Model (PALM) can resolve both the structural details of complex urban surfaces and turbulent eddies larger than 10 meters in size (Pereira et al., 2021). The necessity for sophisticated, high-resolution modeling is validated by the wide variation in effectiveness and the high context dependence observed across different studies (Khan et al., 2020). Such models are crucial for identifying specific pollution pathways and generating vulnerability maps, thereby informing the placement and design of targeted NbS interventions in zones most impacted by emissions (Gopal et al., 2020).

4. The Biogenic Volatile Organic Compound (BVOC) Trade-off and Strategic Species Selection

The implementation of urban vegetation introduces an ecological complexity: the emission of Biogenic Volatile Organic Compounds (BVOCs), which presents a critical trade-off that urban planners must address.

4.1. BVOC Emissions: Mechanisms and Contribution to Secondary Pollutant Formation

Although vegetation generally improves air quality by removing primary pollutants, certain plant species emit BVOCs, such as isoprene and monoterpenes . This natural emission stream can negatively impact air quality in specific urban contexts. In environments characterized by high concentrations of anthropogenic precursors, specifically Nitrogen Oxides (NOx), these BVOCs can participate in photochemical reactions. These reactions lead to the formation of harmful secondary air pollutants, particularly ground-level ozone (O3) and Secondary Organic Aerosols (SOA) (Chowdhury et al., 2025).

Empirical studies confirm that the high O3 formation potential arising from vegetation BVOC emissions is primarily dominated by isoprene, whereas SOA formation is also influenced by lower emissions of monoterpenoids and sesquiterpenoids (Rissanen et al., 2025). This photochemical mechanism means that the creation of green spaces, if not ecologically informed, could potentially offset some of the air quality benefits achieved through pollutant deposition and uptake (Marando et al., 2025). Furthermore, there is a recognized lack of in-depth research on the atmospheric chemistry of BVOCs and the synergistic effects of multiple influencing factors, posing obstacles to effective management (San et al., 2025).

4.2. Strategic Species Selection and Management

To mitigate the BVOC trade-off, careful species selection is mandatory for NbS design, especially in pollution-vulnerable urban areas. The strategy involves prioritizing low-BVOC emitting species where anthropogenic precursor concentrations (e.g., NOx) are high, such as in high-traffic street canyons (Mashanye et al., 2025).

While BVOC risk must be managed, research also highlights specific species that exhibit high removal efficiencies for primary pollutants. For example, *Chlorophytum comosum* (Spider plant) has demonstrated substantial removal capacity, achieving 56.04% removal efficiency for PM2.5 (Gawrońska & Bakera, 2015). Similarly, *Epipremnum aureum* (Pothos) has shown quantifiable PM removal rates. Empirical measurements of BVOC emission potentials generally align with established emission databases, supporting the use of database estimates for urban trees. However, tree-to-tree variation in emissions can be large (Rissanen et al., 2025).

An effective management approach must extend beyond simple species selection to include strategies that protect trees from BVOC-inducing stresses (Rissanen et al., 2025). Factors such as heat, drought, and environmental pollutants can elevate tree stress, which in turn leads to increased BVOC emissions (Rissanen et al., 2025). Maintaining healthy urban ecosystems, therefore, becomes an active component of air quality management. The strategic selection must be contingent upon a rigorous ecological assessment of local atmospheric conditions, balancing pollutant removal efficiency against secondary pollutant formation risk (Rao et al., 2025).

Table 2 illustrates the necessary balancing act between pollution removal and secondary pollutant formation potential.

Table 2.1 Air Quality Trade-offs in Urban Tree Species Selection

Species Category	**Primary BVOC Emission**	**Negative AQ Impact (in presence of NOx)**	**NbS Design Implication**
High BVOC/High O3 Precursor	Isoprene, Monoterpenes	Ground-level O3 and SOA formation Rissanen et al., 2025)	Avoid in high-traffic/high NOx areas (e.g., street canyons)
Low BVOC/High Uptake	Low or non-isoprene emitters	Minimal or none	Preferred species for pollution hotspots and dense urban areas
High Removal Species (e.g., *C. comosum*)	Variable/Context-dependent	Managed to minimize stress-induced emissions	Use for localized mitigation; require rigorous maintenance (Rissanen et al., 2025; Gawrońska & Bakera, 2015)

5. Design Optimization of Green Infrastructure for Targeted Mitigation

The effectiveness of Nature-Based Solutions is highly contingent on their physical geometry and strategic placement within the complex urban environment. Optimized design transforms passive green space into active air quality assets.

5.1. Roadside Vegetation Barriers: Geometric Requirements and Performance

Roadside vegetation barriers, particularly those implemented along high-volume roadways, can significantly improve near-road air quality, provided they are designed according to strict geometric criteria (U.S. Environmental Protection Agency, 2016). Research into best practices emphasizes that for a barrier to achieve greater reductions in downwind pollutant concentrations, it must be tall, thick, and dense (Mashanye et al., 2025).

The primary functional requirement of an effective barrier is aerodynamic impedance. The barrier must be designed to impede the entire plume air flow from the highway, similar to a solid noise barrier (U.S. Environmental Protection Agency, 2016). Studies suggest that walls 4 meters or taller provide sufficient height for air quality improvement. The thickness of the vegetation is equally crucial, as it forces the airflow over the barrier for a longer distance and increases the separation distance between the air pollution source and the downwind receptors (U.S. Environmental Protection Agency, 2016). Generally, studies reporting decreased near-road pollutant concentrations achieved a minimum thickness of approximately 5 meters, with many effective designs approaching 10 meters or more (Rissanen et al., 2025). The requirement for high density and specific geometry confirms that the core principle for reducing concentrations in near-road microenvironments is large-scale turbulence modification and pollutant advection, rather than purely relying on deposition on the leaf surface.

5.2. Distributed GI Systems: Hedges, Walls, and Green Roofs

Beyond large roadside barriers, distributed Green Infrastructure (GI) elements offer scalable solutions for dense urban areas. Hedges, green walls, and green roofs are consistently reported as the most effective GI practices for air quality improvement in densely built environments Green roofs contribute to air quality by providing shading, deflecting solar radiation, and releasing moisture through evapotranspiration, which helps reduce the Urban Heat Island (UHI) effect . This microclimate regulation further assists in the reduction of ground-level ozone and particulate pollution (Rissanen et al., 2025). Localized interventions, such as dense barriers covered in climbers, have demonstrated the capacity to reduce PM concentrations by up to 44% (NatureScot, 2023).

However, the current assessment of the full spectrum of green-blue-grey infrastructure (GBGI) types shows inconsistent reporting (Frontiers in Environmental Science, 2024). Only 22 out of 51 assessed GBGI types provided relevant air pollution efficacy data (Frontiers in Environmental Science, 2024). Street trees remain the most studied GI type (61% of studies focusing on street canyons) (Jan et al, 2024). This inconsistency highlights a crucial standardization gap. The wide variation in methodologies and habitats across local-scale studies prevents meaningful comparison and the development of universal guidelines (MDPI, 2020). Optimized GI design depends on thoughtful species selection, integration with the surrounding urban form, and regular maintenance to sustain pollutant removal efficiency and prevent the resuspension of captured particles (Marando et al., 2025)

6. Engineered Nature-Based Systems: Biofilters and Constructed Wetlands

In addition to passive urban forestry, advanced "Green Technologies" hybridize biological processes with engineering controls to manage concentrated pollutant streams, often utilized in industrial or specialized urban settings.

6.1. Biofiltration Technologies for VOC and Odor Control

Biofiltration represents a current, sustainable pollution management strategy that is highly effective for removing dilute gaseous contaminants, including odors and Volatile Organic Compounds (VOCs), from industrial air streams (Kolekar et al., 2019; MDPI, 2022b). This technology has gained global acceptance due to its low capital cost, straightforward operation, high reduction efficacy, and minimal energy requirements (MDPI, 2022b).

The underlying mechanism involves the adsorption of contaminants onto a porous medium (often compost, soil, or synthetic material) (MDPI, 2022b). Once adsorbed, the pollutants are metabolized by immobilized microorganisms (bacteria and fungi) to produce benign outcomes, such as small amounts of carbon dioxide and water vapor (Kolekar et al., 2019). Biofilters excel in treating dilute gas streams in a cost-effective manner compared to high-temperature or chemical technologies (Rao et a., 2025). The performance of biofiltration techniques is dictated by crucial operational factors, including the medium’s moisture content, the gas residence time, and maintaining an optimal microbial environment (MDPI, 2022b). The centrality of managed microbial activity in biofiltration demonstrates that engineered microbial action is a core component of advanced NbS performance for chemical breakdown, particularly for complex organic pollutants (Mashanye et al., 2025).

6.2. Constructed Wetlands (CWs) and Multi-Media Systems

Constructed Wetlands (CWs) are integrated, engineered systems designed to duplicate the pollutant removal processes found in natural wetlands, leveraging water, plants, microorganisms, and substrate to improve water quality (University of Arizona Water Resources Research Center, 2003). While traditionally focused on wastewater treatment, CWs employ mechanisms relevant to air and volatile contaminant control.

For emerging contaminants, and potentially airborne pollutants, CWs leverage a combination of complex biogeochemical systems, including sorption, photodegradation, microbial biodegradation, and phytoremediation (MDPI, 2022a). Specifically, the mechanism of phytovolatilization is pertinent, wherein contaminants are taken up by the plants' biomass and subsequently transpired through the leaves, releasing them into the atmosphere, often in a less harmful form (Iowa State University, 2003).

CWs offer significant opportunity for developing highly efficient co-treatment systems. For instance, incorporating specific engineering enhancements, such as plenum aeration and saturated zones in Vertical Subsurface Flow (VSSF) CWs, enhances microbial functions like nitrification and overall pollutant removal efficiency (MDPI, 2023; Celletti et al., 2025). These hybrid systems, such as stormwater biofilters incorporating aeration, maximize resource efficiency by managing multiple urban fluxes (water, nutrients, metals, and air contaminants) simultaneously, proving that NbS can be highly engineered for comprehensive urban infrastructure management (Celletti et al., 2025).

7. Policy Integration, Economic Valuation, and Pathways for Scaling NbS

To transition Nature-Based Solutions from localized projects to mainstream infrastructure, governance structures, economic valuation, and strategic planning must be overhauled to address systemic challenges.

7.1. Economic Valuation and Public Health Benefits

The economic value of forests and green spaces as public goods is frequently underestimated, largely due to their non-rivalry and non-exclusiveness attributes (Choi et al., 2025). However, quantitative economic valuation can demonstrate the crucial benefits, including cleaner air, water, and flood control (Rao et al., 2025).

Monetary valuation provides tangible data for planning and budgetary justification by quantifying the public health benefits derived from reduced exposure to air pollutants (D’Alpaos et al., 2023). For example, studies in South Korea estimated that the monetary value of air quality improvement provided by forests for five major air pollutants (SO2, NO2, PM10, PM2.5, and O3) reached trillions of KRW annually between 2014 and 2017 (Choi et al., 2025). The methodology for deriving these figures involves multiplying the tree canopy cover within an area by the annual health savings realized per hectare of tree canopy cover, thereby quantifying the avoided economic burden associated with poor health (D’Alpaos et al., 2023). This quantification is essential for integrating the environmental and health aspects of NbS into fiscal decision-making (D'Alpaos et al., 2023).

7.2. Global Challenges in Mainstreaming and Governance Gaps

A recent synthesis of NbS research identifies eight cross-cutting challenges that hinder the global scaling and mainstreaming of these solutions (McPhearson et al., 2025). These critical areas are categorized as: Conceptual, Thematic, Geographic, Ecological, Inclusivity, Health, Governance, and Systems challenges (Mashanye et al., 2025).

The Governance Challenge is particularly acute in urban settings, where NbS are often excluded from city planning processes (European Commission, 2015; Ecology and Society, 2023). Literature suggests that urban policymakers and planners must integrate NbS into urban development strategies to address adaptation, cultural benefits, and regulating ecosystem services such as air quality and UHI mitigation (Ecology and Society, 2023). Effective integration requires inclusive participation processes involving all relevant stakeholders, especially the citizens (European Commission, 2015; Ecology and Society, 2023).

The Inclusivity Challenge underscores a major concern: equitable access. Socially disadvantaged groups are often more vulnerable to the negative impacts of air pollution and urban heat, and concurrently, are likely to reside in less green neighborhoods (European Commission, 2015; Ecology and Society, 2023). Therefore, for NbS to support sustainable and inclusive city growth, justice and equity must be central to the urban approach (McPhearson et al., 2025). Failure to address this disparity undermines the long-term social sustainability of the solution (Rao et al., 2025).

Table 7.1 Synthesis of Global Challenges and Critical Pathways for Scaling Urban NbS

NbS Implementation Challenge	Nature of the Challenge	Critical Pathway for Scaling Up
Conceptual, Thematic, Geographic	NbS is an umbrella concept lacking common definition; uneven geographical knowledge (Global South gaps) (McPhearson et al., 2025)	Foster new NbS research, technological innovation, and learning (McPhearson et al., 2025)
Ecological, Health, Systems	Need for local ecological knowledge; addressing coupled systems (air, heat, water) (McPhearson et al., 2025)	Ensure a systems approach to NbS planning and implementation (McPhearson et al., 2025)
Inclusivity, Governance	Exclusion of marginalized groups; fragmentation across planning sectors; need for political buy-in (European Commission, 2015; Ecology and Society, 2023; McPhearson et al., 2025)	Increase financing and political will for diverse NbS implementation (McPhearson et al., 2025)
Knowledge Sharing	Lack of standardized reporting and transferability of findings across regions (McPhearson et al., 2025)	Build a global NbS alliance for sharing knowledge (McPhearson et al., 2025)

7.3. Critical Pathways for Scaling and Integrated Financing

Based on the global assessment of challenges, four critical pathways have been identified to successfully scale NbS implementation (McPhearson et al., 2025): 1) Fostering new NbS research, technological innovation, and learning; 2) Building a global NbS alliance for sharing knowledge; 3) Ensuring a systems approach to planning and implementation; and 4) Increasing financing and political will for diverse NbS implementation (McPhearson et al., 2025).

Overcoming the financial barrier (often associated with high capital costs (Kolekar et al., 2019; MDPI, 2022b)) can be achieved through strategic spatial targeting. The use of a **risk index** for NbS allocation enables highly targeted interventions that prioritize areas of greatest human health risk (D'Alpaos et al., 2023). This approach has been shown to dramatically improve cost-effectiveness and equitableness, potentially allowing for significant budget savings (e.g., reducing the surface area of interventions by 67%) with only a negligible loss in the return for human health (Rao et al., 2025). This approach validates the necessity of sophisticated spatial data analysis for both performance optimization and budgetary justification.

8. Conclusion and Future Research Directions

Nature-Based Solutions, encompassing plants, urban forests, and engineered green technologies, offer a scientifically validated and economically beneficial pathway for urban air pollution control. The efficacy of NbS is contingent upon a nuanced understanding of their dual function: specific mechanistic removal (dry deposition for PM, stomatal uptake for gases) and atmospheric modification (dispersion enhancement and LST reduction). Crucially, the implementation must be ecologically informed to manage the BVOC trade-off and geometrically optimized (e.g., tall, dense roadside barriers) to ensure effective pollutant impedance and dispersion.

Despite demonstrated local successes (e.g., 44% localized PM reduction (NatureScot, 2023)), wide-scale integration remains hampered by systemic governance and quantification challenges. To fulfill the potential of NbS, four major research and implementation priorities must be addressed:

1. **Integrated Modeling and Prediction:** Future research must focus on developing integrated models that couple atmospheric chemistry, urban climate (LST), and vegetation physiology. These models are required to predict the net effectiveness of NbS accurately, accounting for the dynamic interplay between pollutant removal, dispersion, and the negative consequences of BVOC emissions under various meteorological scenarios (Rao et al., 2025)
2. **Long-term Efficacy and Durability:** Establishing long-term, sustained monitoring programs is essential to assess the sustained air quality impacts of NbS over decadal timescales. This is necessary to understand the long-term resilience of plant species and the durability of removal mechanisms under prolonged exposure to stress and pollution (San et al., 2025).
3. **Quantification and Standardization:** To facilitate knowledge sharing and develop generalized guidelines, there is an urgent need to develop standardized methodologies for assessing local-scale efficacy across different habitats. This will enable meaningful comparative studies and meta-analyses, overcoming the current limitations imposed by inconsistent reporting (Celletti et al., 2025; MDPI, 2020).
4. **Policy, Equity, and Cost-Effectiveness:** Comprehensive socio-ecological assessments must be performed to ensure NbS implementation prioritizes disadvantaged communities, thereby meeting the fundamental requirements of justice and equity (European Commission, 2015; Ecology and Society, 2023; McPhearson et al., 2025). Concurrently, governance frameworks must leverage advanced data analysis, such as risk-index allocation, to optimize cost-effectiveness and maximize public health returns on investment (D'Alpaos et al., 2023).

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