REVIEW ARTICLE

Green Plants as a Sustainable Solution to Air Pollution

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Abstract

In today's global context, the escalation of air pollution stands out as an immensely critical environmental challenge that has attained a worldwide magnitude. This pressing issue not only impacts every living organism on our planet but is also intricately linked to the phenomenon of climate change. The significant increase in vehicular traffic, rapid urbanization, and infrastructure development have indirectly contributed to a higher concentration of harmful gaseous and particulate pollutants in the atmosphere, posing serious risks to human health. Extensive research has thoroughly documented the adverse effects of these air pollutants, with mortality and morbidity rates varying depending on the type of pollutant and the duration of exposure. However, amidst this crisis, green plants emerge as a cost-effective and promising solution to combat environmental pollution, presenting several additional benefits. Specifically, pollution-tolerant plant species are crucial in reducing ambient air pollution and the urban heat island effect. To assess a plant's tolerance towards air pollution, experts use the air pollution tolerance index (APTI), which calculates crucial factors such as ascorbic acid, total chlorophyll, pH, and relative water content in the plant. This determination provides a reliable method for categorizing plants into either tolerant or sensitive types in the face of air pollution. Moreover, the morphological characteristics of leaves, such as stomata distribution and density, cuticle thickness, and trichome density, play an essential role in adsorbing and absorbing particulate matter from the air. These inherent qualities further enhance plants' potential to combat air pollution in a sustainable manner, making them valuable assets for the future.

In light of this, the present review highlights the impressive capacity of plants to remediate air pollutants and explores the various strategies employed in this crucial endeavor. By leveraging the remarkable capabilities of green plants, we have the opportunity to address the air pollution crisis and embrace a sustainable path for the times to come. These remarkable organisms could be the sustainable saviors we need to protect our environment and secure a healthier future for all.

Keywords: Air pollution, Phylloremediation, Air Pollution Tolerance Index (APTI), Climate change, Leaf morphology

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Introduction

Rapid urbanization and infrastructure development during recent decades has contributed to increased anthropogenic pressures on the environment. The outcome of this situation is 'air pollution' which is posing a threat to both human and ecosystem health, requiring practical, sustainable remediation methods (Leonard *et al.,* 2016). Shockingly, the most recent estimates of mortality due to ambient air pollution (AAP) stand at 8.8 million deaths annually (Lelieveld *et al.,* 2020). Although human existence on earth is very recent as per the geological time scale, anthropogenic activities have increasingly caused a substantial impact on the earth by polluting the environment. Global environmental pollution is an international public health issue with multiple aspects like socio-economic and lifestyle implications (WHO, 2019). Sadly, the air we breathe is polluted much above the threshold limit owing to rapid industrialization, urbanization, the burning of fossil fuels, and other human activities (Lee *et al.,* 2021). There is substantial evidence that rising air pollution is also linked with global climate change as many air pollutants and greenhouse gases (GHG) have not only common sources, but their interaction in the atmosphere also exhibits synergistic effects causing environmental impacts at local and global levels (Bytnerowicz *et al.,* 2007; D'Amato *et al.,* 2016). The World Health Organization (WHO) estimated in 2019 that about 7 million premature deaths were attributed annually to the effects of ambient and household air pollution. Prior to that in 2016, the World Health Organization had reported that more than 92% of the world's population is exposed to air pollutants exceeding the limits prescribed by WHO. This report further suggests that air pollution is the largest environmental risk factor, which leads to increased morbidity and mortality. Major air pollutants include particulate matter (PM), nitrogen oxides (NO_x), sulfur oxides (SO_x), ground-level ozone (O_3), and volatile organic compounds (VOCs) (Wei *et al.,* 2017, Archibald *et al.,* 2017). Metropolitan cities suffer from high pollution from multiple emission sources, especially in India. The United Nations Organisation has predicted that by the year 2050, 2.5 billion people will inhabit urban areas, with Asia and Africa contributing to almost 90% of the increase in air pollution (United Nations *et al.,* 2019).

It is unequivocal that the first step towards reducing ambient air pollution is to eliminate/reduce anthropogenic emissions and the second step is remediation of the existing pollutants. Recently, green plants are emerging as rescuers of humanity with their ability to remediate the gargantuan levels of air pollution. Remediation of air pollution by plants is the most environment-friendly and cost-effective approach and is commonly known as phytoremediation. All parts of plants comprising of plant shoots or the above-ground organs of plants together with

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a variety of bacteria, yeasts, and fungi that colonize them are referred to as phyllosphere (Last, 1955). The potential of plant leaves and leaf-associated microbes to remediate air pollutants is commonly known as phylloremediation, a term first coined by Sandhu *et al.,* (2007).

The mechanism of phytoremediation in the air is based on the absorption and degradation of airborne pollutants by the leaf structure and the metabolic activities of plants (Han *et al.,* 2022). Plants reduce the mobility, toxicity, and volume of the contaminants through varied mechanisms such as: accumulation, immobilization, volatilization, and degradation. These biological processes are driven by solar energy alone, making phytoremediation a cheaper and more sustainable method of remediation compared to engineering-based remediation methods (Lee *et al.,* 2021). The absorption of pollutants is mainly carried by above-ground plant surfaces like the stomata of leaves (Kulshreshtha *et al.,* 2009). Pollutants' adsorption depends on various anatomical structures of these leaves like the waxy cuticle, hair, etc. Further degradation of pollutants proceeds with the decomposition of foreign pollutants by various plant metabolites like catalase, dehalogenase, etc. (Rachmadiarti *et al.,* 2019). Novel communities of plant species that emerge and thrive in polluted conditions may represent a promising opportunity to address air pollution and climate change adaptation and mitigation through the planting design and management of urban green space (Teixeira *et al.,* 2022). The present review primarily focuses on the current status of sustainable remediation strategies for the ever-increasing air pollution along with briefly discussing the sources and effects of pollution.

Air Pollution: Ambient and Indoor

The WHO defines air pollution as the contamination of outdoor (ambient) and indoor (household) environments by any chemical, physical, or biological agent that modifies the natural characteristics of the atmosphere (Roberts, 2021). Air pollution is caused by a variety of natural and anthropogenic sources of emissions, with the latter becoming increasingly dominant ever since the advent of industrialization. The combustion of fossil fuels and biomass for the generation of energy is the greatest contributor to ambient air pollution (AAP). Pollutants generated directly from the process of combustion are the primary pollutants (such as Particulate Matter), while those formed in the air as a result of chemical reactions with other pollutants and atmospheric gases are known as secondary pollutants. These can include sulphur and nitrogen oxides, carbon monoxide, soot particles, and smaller quantities of toxic metals, organic molecules, and radioactive isotopes.

In addition to AAP, indoor or household (indoor) air pollution (HAP) too poses a serious health risk for nearly 2.4 billion people using biomass, firewood, kerosene fuels, and coal (WHO, 2021) for cooking as well as heating their homes. Amoatey *et al.,* 2018 reported that indoor air pollution primarily results from the infiltration of ambient air pollutants into residential buildings, poor ventilation, burning of biomasses (incense, repellents etc.), and overcrowding. Many Asian countries have a tradition of incense burning in temples and households, which releases smoke generating respirable particulate dust, carbon dioxide, carbon monoxide, volatile organic compounds (VOC's), and carcinogens such as PAHs, carbonyls, and benzene (Jilla and Kura, 2017). Other sources of indoor air pollution include smoking, spraying of insecticides and pesticides, perfume, deodorants, cleaning agents, and building materials (Apte and Salvi, 2016). Certain residential locations in the United States have been shown to contain numerous NMVOCs (non-methane volatile organic compounds), including hazardous air pollutants, such as benzene resulting from unburned natural gas supplied to indoor gas appliances and outdoor gas appliance lines (Michanowicz *et al.,* 2022).

Pollutants Responsible for Ambient Air Pollution and Climate Change

The United States Environment Protection Agency has identified six pollutants as "criteria" air pollutants. These six pollutants are particulate matter (often referred to as particle pollution), carbon monoxide, lead, nitrogen oxides, ground-level ozone, and sulfur oxides (https://www.epa.gov/criteria-air-pollutants, 2023). The category and concentration of these pollutants vary in each country subject to the source of pollutants and the local climate.

Particulate matter is the primary (but not the only) component of air pollution which is made up of particles of many different sizes and chemical compositions, depending on the wide range of natural and anthropogenic sources (Holman, 1999). The focus in recent decades has been on particles with aerodynamic diameters of less than or equal to 2.5 ($PM_{2.5}$) or 10 µm (PM_{10}) (WHO, 2021). Though the coarse particles originate from natural sources and anthropogenic activities, fine particles mainly originate from vehicle emissions (gasoline and diesel), combustion, and industrial processes (Chow *et al.,* 2006). Nano-size particles originating from traffic sources are one of the most harmful components of ambient PM. Such particles' physical properties are responsible for being highly reactive toward biological surfaces and structures (Drakaki *et al.,* 2014).

Besides increasing particulates in the environment, several of the industrial and agricultural activities of humans have also greatly increased biologically active nitrogen compounds and sulphur oxides in the air, generated mainly by combustion (Falusi *et al.,* 2016). Internal combustion engines, fossil fuel-fired power stations, and industrial combustion are the main contributors of NOx emissions. All the fossil fuels extracted from the ground contain some amount of sulphur, especially burning coal and petroleum contribute majorly to the oxides of sulphur (SOx) in the air. Natural gas, petrol, and diesel fuels are known to cause less pollution owing to relatively low sulphur content. Combustion processes are also responsible for a large percentage of carbon monoxide emanation in both on-road vehicles and in diverse off-road uses, comprising the principal sources. Ground-level ozone is another potent pollutant created by chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs). Besides these sources of air pollution, volatile organic carbons (VOCs) comprising of a wide range of chemical compounds, including hydrocarbons (alkanes, alkenes, aromatics), oxygenates (alcohols, aldehydes, ketones, and ethers) and halogen-containing species also contribute majorly to the ambient air pollution. Methane, an important VOC, especially in India, is increasingly being considered separately from the other VOCs due to its substantial contribution to global warming. Polyaromatic hydrocarbons (PAHs) are among the most widespread organic pollutants in the air and generated primarily by residual wood burning, vehicular exhaust (especially diesel engines) and from smoke resulting from the combustion of organic material (including cigarette smoke) (Drakaki *et al.,* 2014).

Different air pollutants in India and their sources were investigated by Sharma and Kumar in 2016, and it has been estimated that though the NOx emissions are primarily dominated by the transportation sector (35%) followed by power utilities (22%), the emissions from SO_2 are greatest due to coal combustion. Emissions from particulate matter are mainly contributed by the industrial (43%) and domestic (29%) sectors. The transportation sector too contributes about 4% of PM_{10} emissions at the national level but this is mainly concentrated in urban areas. Rural regions are seen to generate roughly 8% of total PM_{10} emissions from the open burning of agricultural leftovers, popularly referred to as stubble burning. Power plants are another culprit adding substantial PM_{10} pollution.

It is a well-known fact that many traditional air pollutants (APs) and green house gases (GHGs) have common sources and interact in the atmosphere on a global level. CO_2 is the main driver contributing to global warming, followed by methane (CH_4), halocarbons, and nitrous oxide (N_2O) (Hedhly *et al.,* 2009). Depending on their composition and concentration, aerosols and particulate matter (PM) affect the climate. Climate change, especially high radiation and temperature, promote the intensification of tropospheric ozone (O_3), carbon monoxide (CO), and nitrogen oxides (NOx). Of these, O_3 itself is a potent GHG that indirectly influences the lifetimes of other GHGs, such as CH_4. Methane emissions emitted up to and including 2019 account for approximately a third of the warming effect of all well-mixed greenhouse gas emissions and for 45% of the net warming effect of all anthropogenic activities (Fuller *et al.,* 2022). According to the Intergovernmental Panel for Climate Change (IPCC 2021), the global surface temperature was 1.09°C higher in period from 2011–2020 than in 1850–1900.

Air Pollution and Public Health

Air pollution has become an important concern for human health as it is responsible for a wide range of diseases/ailments like skin disorders, chronic obstructive pulmonary diseases (COPDs), non-communicable diseases, infant mortality etc (Roberts, 2021), It accounts for 22% of all deaths from cardiovascular diseases, 26% of deaths from ischaemic heart diseases, another 25% from stroke, 53% from COPDs, and 40% of deaths from lung cancer (Reddy and Roberts, 2019). Long-term exposure to airborne PM is directly associated with various potentially fatal childhood diseases, including post-neonatal infant mortality (Laden *et al.,* 2006). According to an epidemiological study carried out in 2012 by CPCB along with Chittranjan National Cancer Institute, Kolkata, people residing in Delhi, the pollution capital of the world, are more susceptible to higher respiratory symptoms, reduced lung function, hematological and immunological changes, geno-toxicological and neurobehavioral symptoms (CPCB and MoEFCC, 2012). Chronic obstructive pulmonary disease (COPD) which is explicitly induced by increased PM_{10} in ambient air is one of the leading causes of death, responsible for 6% of total deaths in the world (WHO, 2020). Chronic exposure to noxious gases in genetically susceptible individuals leads to significantly high morbidity and mortality. In India too, the epidemiological projections of COPD reflect a rising trend. Besides exposure to air pollution, active or passive smoking, or being vulnerable to biomass smoke, or occupational dust and chemicals are some of the causes leading to COPD (Ghosh *et al.,* 2022). A recent study of PM in China revealed that a 10 $\mu g/m^3$ increase in PM_{10} reduces life expectancy by 0.64 years (Ebenstein *et al.,* 2017). Furthermore, air pollution may decrease physical activity levels during high air pollution episodes or may even prevent people from engaging in physical activity in highly polluted environments (Tainio *et al.,* 2021).

The human skin (though playing the role of a barrier) is also one of the first and major targets of air pollutants. Major air pollutants with effects on the skin include solar ultraviolet radiation (UVR), polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), nitrogen oxides (NOx), particulate matter (PM), and cigarette smoke. Automobile exhaust (especially diesel engines) is the main source of atmospheric PAH which has been implicated in the development of skin cancer (Drakaki *et al.,* 2014). Apart from being responsible for skin aging (photoaging), it has been linked, along with UVB, in the development of skin cancers such as malignant melanoma, basal cell carcinoma (BCC), and squamous cell carcinoma (SCC) (photo-carcinogenesis). Long-term exposure of skin to PM-bound PAHs either through hair follicles or trans-epidermal absorption, may lead to oxidative stress and skin aging (Vierkötter *et al.,* 2010).

While air pollution affects almost the entire earth, there is significant spatial variance in pollution levels. The Lancet commission report published by Fuller *et al.* (2022) on pollution and health stated that more than 90% of these pollution-related deaths occur in low-income and middle-income countries. India is known to be the home to 11 of the 15 most polluted cities in Central and South Asia in 2021. Delhi saw a 14.6% increase in $PM_{2.5}$ concentrations in 2021, rising to 96.4 $\mu g/m^3$ from 84 $\mu g/m^3$ in 2020 (IQAir 2021). In 2019, 1.67 million deaths were attributable to air pollution in India, accounting for 17.8% of the total deaths in the country. The majority of these deaths were from ambient particulate matter pollution (0.98 million) and household air pollution (0.61 million). In 2019, Delhi had the highest per-capita economic loss due to air pollution, followed by Haryana, with 5.4 times variation across all states (Pandey *et al.,* 2021). Urbanization significantly influences local air quality by the process of altering land use, population expansion, and Urban heat island (UHI) effect (Čeplová *et al.,* 2017; Manisalidis *et al.,* 2020; Liang and Gong, 2020; (Narain *et al.,* 2020)). Urban Heat Island effect (UHI) is one of the most obvious effects of urbanization with urban areas typically experiencing higher temperatures than their surrounding landscapes.

Air Pollution and Plants Health

Terrestrial plants being fixed at a location, unlike animals are forced to withstand ambient climate changes arising from the rising levels of air pollution. Consequently, a plant's phenology encompassing life-cycle events is susceptible to climate change. Species across a wide range of taxa and habitats are shifting phenological events in response to climate change. While advances are common, shifts vary in magnitude and direction within and among species, and the basis for this variation is relatively unknown (Chmura *et al.,* 2019). Vegetation responses to urbanisation have been studied extensively for temperate cities where Urban Heat Islands (UHI) result in earlier start dates of the growing season and lead to longer growing season durations than surrounding rural areas (Jochner and Menzel, 2015). Other consequences are an early bud break and flowering in urban environments (Li *et al.,* 2022).

Undoubtedly, the air pollutants have altered the earth's atmosphere, leading to an overall negative impact on plant health. There is a silver lining to all the negative effects in terms of tolerance to pollutants by some plants which are known to react to different environmental stresses. The most evident response in terms of tolerance has been primarily shown by the leaves (Mukherjee *et al.,* 2019) which are known to remediate pollutants to some extent. On the other hand, it is the leaves only which exhibit visible damage owing to pollution. In general, the plants experience several physiological changes before exhibiting visible damage to leaves when exposed to air pollutants. These pollutants in combination cause greater or synergistic effects on plant growth affecting their physiological behaviour (Falusi *et al.,* 2016).

Of all the pollutants, particulate matter pollution is notably the most harmful of all pollutants as it disrupts major plant functions and triggers oxidative stress (Singh *et al.,* 2009; Rai *et al.,* 2013). Leaf stomata are considered to be key openings for the exchange of gases, including CO_2, but when the Tropospheric or ground-level ozone penetrates via the stomata of plants, it causes them to close, eventually preventing CO_2 exchange and reducing photosynthesis (Manisalidis *et al.,* 2020). Gaseous pollutants, such as sulphur dioxide, nitrogen dioxide, and tropospheric ozone, can also potentially decrease crop output and nutritional quality (Agrawal *et al.,* 2003; Peng *et al.,* 2004). Some of the early conclusions in agricultural systems stated that an increased CO_2 concentration will lead to a fertilizing effect, subsequently leading to an increased yield. However, it was realized later that the yield was lower than anticipated as it was not solely the effect of CO_2 but also resulted from the interaction of CO_2 with other climatic factors. This is very much in line with the conclusion drawn by Hedhly *et al.,* (2009) stating that the moderate increase in temperature might result in an increase in average yields in temperate and high-latitude regions, but will reduce the yield in semi-arid and tropical regions. Recent research shows that some pollutant particles get absorbed into the tree, though most of these particles are retained on the plant surface, some may get dropped to the ground with the falling leaves and twigs or may even be washed off by rain. The accumulation of particles on the leaves can affect photosynthesis and therefore, potentially affect pollution removal by trees. Air pollution can directly affect plants via leaves or indirectly via soil acidification. Although plants serve as a sink for PM deposition, this deposition can often lead to specific morphological, physiological, and biochemical reactions (Rai *et al.,* 2013; Rai 2015).

Mitigation of Ambient Air Pollution

Green plants are the most potential candidates for mitigating air pollution as they improve air quality in both direct and indirect ways. First of all, they play a vital role in directly removing pollutants from the air and are often considered as the "green lungs" of an ecosystem because of their ability to absorb carbon dioxide and emit oxygen. Secondly, they also behave as 'liver' to an ecosystem by filtering atmospheric pollutants like sulphur dioxide and nitrogen dioxide through their leaves. Trees are particularly effective at removing particulate matter (PM), both by absorption as well as adsorption.

The trees can also help by shading surfaces and reducing Urban Heat Island effect in cities. If trees shade buildings, it reduces the need for conventional air conditioning and subsequently reduces the emissions of greenhouse gases that come with it. Lower temperatures also reduce the levels of harmful pollutants like ground level ozone that commonly spike on hot days in urban areas.

Rapid urbanisation and increasing awareness of the effects of the natural environment on our health have motivated numerous studies on outdoor land plants as interventions to protect our health from ambient air pollution at different scales (Diener and Mudu, 2021). In response to increasing global urbanization, cities are progressively implementing green infrastructure and nature-based solutions to deliver specific ecosystem functions (Teixeira *et al.,* 2022). A multifunctional network of green spaces in cities can support both ecological and social goals due to their potential role in adapting and reducing climate change effects in cities (Klaus and Kiehl, 2021; Teixeira *et al.,* 2022).

Green spaces by and at large can cause PM to change trajectories, speed, and other properties or to be removed from the air temporarily or permanently. The vegetation's leaves are found to be the most instrumental part of the plant for air pollution reduction. These green spaces or the green infrastructure is a strategically planned network of natural and semi-natural areas that deliver a wide range of ecosystem services, support a green economy, and improve the quality of life. The term, 'Green infrastructure (GI)' was coined by Benedict and McMahon in 2006 to provide an antonym to grey infrastructure and emphasize GI as our life-support system. While the grey infrastructure comprises the built components of cities, including buildings, roads, pavements, sewers and other structural utilities, the green infrastructure (comprising mainly of green cover) is meant to spatially complement grey infrastructure and at the same time counterbalance some of the negative effects associated with grey infrastructure. According to Hewit *et al.,* (2020) introduction of the so-called Green Infrastructure (GI) is a beneficial solution for improving air quality in urban spaces. This reduces the concentration of particulate matter at ground level without the need to impose restrictions on road traffic and take other actions to address this problem. As trees accumulate more pollutants than grasses, we need to extensively plant more trees to increase the GI. Moreover, apart from the quantity of particulates accumulated by trees, there is also a major difference in particle deposition rate between trees and grasses, it being 11 $mm \times s^{-1}$ for urban trees and 3 $mm \times s^{-1}$ for grasses. Dry deposition on city trees is ~70% of the total deposition, and for grass is a meager 25% (Kończak, 2021).

To elaborate further, besides trees and grasses, green infrastructure also encompasses a range of parks, nature reserves, street trees, gardens, river corridors, ponds, green roofs and walls, farmed land and allotments, as well as linking elements such as the 'green corridors' found alongside roadways and railway lines (Cameron and Blanu Sa, 2016). The short-term economic benefits of converting land for development over retaining it as open space have sometimes led to short-sighted vision in urban planning in the country, eventually destroying green spaces. The potential of planting more trees and creating ample green spaces in social and environmental urban sustainability, and its potential in cost-effective climate adaptation and mitigation though of utmost importance, has not been realized fully even in India. Novel communities of plant species that emerge and thrive in the harsh conditions of cities may represent a promising opportunity to address climate change adaptation and mitigation through the planting design and management of urban green spaces (Teixeira *et al.,* 2022).

The roadside trees have the potential to effectively capture the airborne pollutants. With rising awareness about air pollution, the primary purpose of avenue trees has shifted from beautification to the provision of services like air quality improvement, prevention of soil erosion, reduction in stormwater and energy conservation in the past years. According to Chaudhary and Rathore (2018), large healthy trees can reduce air pollution by 60 to 70 times than smaller plants. Modeling studies suggest that trees have the ability to remove PM from the air in big cities, for instance, trees planted in the greater London area were estimated to remove 800 to 2,000 tonnes of PM_{10} annually (Tallis *et al.,* 2011), and public trees in Strasbourg, France to remove 11.77 and 4.51 tonnes per year of PM_{10} and $PM_{2.5}$ respectively (Selmi *et al.,* 2016). A study by Nowak *et al.,* 2014 in the United States concluded that trees remove substantial amounts of pollution and can produce substantial health benefits and monetary values, especially the ones present in urban areas.

It is well known that urban green spaces are commonly recognized for their ability to enhance public health through various mechanisms. Wu and Chen (2023) have discovered a negative correlation between the size and fragmentation of green spaces and air pollution levels, particularly concerning $PM_{2.5}$, PM_{10}, and NO_2. Additionally, they observed that densely distributed small green spaces and diverse green space types were associated with increased life satisfaction.

China, another major contributor of air pollution in the world, has put in efforts to mitigate air pollution primarily emanating from its large-scale coal-fired power plants. Though, they have been able to reduce this air pollution by usage of air pollution control devices, commonly referred to as APCDs, these devices result in indirect emissions of CO_2 as they are reliant on electricity (Zhang *et al.,* 2024).

Evergreen shrub species demonstrated superior performance in dust retention compared to deciduous shrub species. As a result, when the primary objective of urban greening is focused on air purification as an ecosystem service, prioritizing evergreen shrub species over deciduous ones may be a more suitable choice.

Karimian and colleagues (2023) suggest cultivating *Sedum reflexum* using biodegradable material, Biogas-digestate (BD) on green roofs in polluted areas as it enhances the tolerance of green roof plants in capturing air pollutants. This recommendation is based on the plant's ability to absorb particulate matter (PMs) and its non-edible nature.

A study was carried out to examine the effectiveness of different interventions, including green screens, air purifiers, and school streets, in reducing exposure to air pollutants in three schools of London. A comprehensive understanding was gained regarding the improvements in air quality both inside and outside the classrooms across three schools. Notably, PM concentration was reduced up to 44% in the playground where a green screen of ivy plants (*Hedera helix*) was installed along the school fences (Abhijith *et al.,* 2022).

A similar experiment was conducted in the heating season, in a school building situated in New Belgrade, Serbia, where the researchers measured concentrations of PM_1, $PM_{2.5}$, and PM_{10} above a green roof and a reference roof (Kostadinović *et al.,* 2023). The green roof exhibited a percentage reduction of 17.6% for PM1, 16.6% for PM2.5, and 7% for PM10 when compared to the reference roof.

A study by Yadav *et al.* (2023) offers recommendations to the relevant authorities and environmental protection organizations regarding the most appropriate plant choices for establishing green belts in residential and commercial zones in the city of Kanpur, India. Based on the Air pollution tolerance index data, *Mangifera indica* (30.54) and *Magnolia grandiflora* (26.53) emerge as the most suitable plant species for commercial areas. On the other hand, for industrial areas, *Lonicera nigra* (37.26), *Psidium guajava* (36.62), and *Azadirachta indica* are identified as the best-suited plant options. These findings aim to assist in the effective planning and implementation of green belts in various urban settings

Although much attention has been paid to understanding particulate matter deposition on green infrastructure (GI), not much emphasis is placed on the leaf traits that might maximise the removal of airborne PM (Corada *et al.,* 2021). For a long time, we have known about phytoremediation, where plants are instrumental in remediating pollutants from air, soil, and water. In 2017, a new term "Phylloremediation" was coined to refer to the remediation of air pollutants fundamentally through plant leaves and leaf-associated microbes. Leaves are actively involved in mitigating air pollution as the leaf structural characteristics like cuticle, epicuticular wax, stomata, and trichomes, together with total leaf area, influence trees and shrubs efficiency in removal of particulates from urban atmosphere. A waxy coating called cuticle occupies the leaves' upper surface, which is instrumental in preventing water from evaporating from the leaves' surface and acts as a barrier to foreign substances (Kirkwood, 1999). The leaf surface has several epidermal outgrowths in various forms, called the trichomes which play roles in mechanical and biochemical defence owing to their physical properties and also by secreting secondary metabolites (Tian *et al.,* 2017). Another important leaf structure -the stomata, small openings on the surfaces of leaves and stems, bounded by a pair of guard cells, control the exchange of gases (most importantly water vapour and CO_2) between the interior of the leaf and the atmosphere (Hetherington and Woodward 2003). Stomata play a key role in accumulating PMs and absorbing various gaseous pollutants like SO_2, O_3, VOCs, and BTX (Wei *et al.,* 2017).

Among broadleaved trees, species with rough leaf surfaces are more efficient in PM capturing as surface roughness interacts mainly with fine and ultrafine particles depending on Brownian diffusion (Baraldi *et al.,* 2019; Hwang *et al.,* 2011). Epidermal trichomes on leaf surface enable leaves to trap bigger size PM, while ridges and grooves of epidermal cells lining, veins projections and stomata with wax rings enable the trapping of smaller particles.

Many researchers have listed various leaf traits that effectively capture PM. These traits include the presence of grooves, folds, small chambers, flocculent projections, long fuzz, short pubescence and wax on the surfaces of the leaves along with trichome density, leaf hair density, wax content (Sæbø *et al.,* 2012; Popek *et al.,* 2013; Shi *et al.,* 2017; Weerakkody *et al.,* 2017; Zhang *et al.,* 2019), leaf wettability (Muhammad *et al.,* 2019), stomata size and distribution (Chaudhary and Rathore, 2018). Each of these traits can remediate particulate matter in the air in one way or another. Several quantitative studies have been carried out to evaluate the most appropriate leaf trait to effectively capture PM (Table 1).

Trichomes on leaf surface enable leaves to trap bigger size PM, while ridges and grooves of epidermal cells lining, vein projections and stomata with wax rings enable the trapping of smaller particles (Baraldi *et al.,* 2019; Xu *et al.,* 2020;). Weerakkody and others (2017) reported that smaller-leaved species can capture PM effectively due to their high leaf rigidity and Leaf Area Index (LAI). Further, it was found that PM capture levels on the leaves' adaxial surfaces are generally higher than abaxial surfaces. This could be due to the orientation of the leaves in space where the adaxial surface gets more exposure to particulates through sedimentation under gravity. Evergreen conifers with needle leaves are considered to be more effective in PM accumulation than broadleaved trees due to their thicker epicuticular wax layer, complex foliage structure, and the potential for accumulating pollutants throughout the year (Beckett *et al.,* 2000). Dry deposition of PM on leaves occurs through different processes (sedimentation under gravity, impaction, interception etc) resulting in different deposition velocities (Weerakkody *et al.,* 2017).

Wei and the group (2017) have directed attention to bioremediation of air pollutants by exploiting the potentials of plant leaves and leaf-associated microbes. According to them, the leaf surfaces summing up to approximately 4 × 108 km^2 on the earth, are a home to more than a thousand bacterial cells. These leaf surfaces along with habituated microbes are able to adsorb or absorb air pollutants, and biodegrade or transform pollutants into less or nontoxic molecules. Unfortunately, the potential of leaves and their associated microbes in remediating air pollution remains largely unexplored.

Corada *et al.,* (2021) have suggested in their review, that leaves with rough, hairy or sticky surfaces with a thin wax layer and large and dense stomas, appear to be more effective

Table 1: Important Leaf traits identified for PM capture by systematic literature review

Sr. No.	*Important Leaf trait*	*Target air pollutants*	*Mode of action*	*Reference*
1.	Stomata size and distribution	Particulate matter	High stomatal index increases gaseous exchange from plant enhancing its tolerance to pollution	Chaudhary and Rathore (2018)
2.	Leaf hair density and leaf wax content	Particulate matter	Small sized PM captured and inhibited from resuspension into air	Sæbø *et al.,* (2012)
3.	Microscopic morphology (grooves, folds, small chambers, flocculent projections, long fuzz, short pubescences and wax on the surfaces of the leaves)	Particulate matter	Increase in PM capture by roughness surface of leaf inhibiting resuspension into air	Shao *et al.,* (2019)
4.	Abaxial surface of leaves	Fine Particulate matter (1-2.5 µm)	Difference in deposition chance of particles on the adaxial and abaxial side and through wind turbulences	Shi *et al.,* (2017)
5.	High trichome density and leaf wettability	Particulate matter (garden)	Trichomes captures bigger size particulate matter and inhibit their resuspension in air and Leaf wettability (contact angle between a water droplet and leaf surface) also influences PM accumulation	Muhammad *et al.,* (2019)
6.	Leaf surface roughness; foliar trichomes	Particulate matter	Ability of leaf to accumulate dust is dependent on the leaf surface and cell morphology. Trichomes play major role in the adsorption of particulate matter and decrease the resuspension of particles on the leaf surface into air significantly	Zhang *et al.,* (2020)
7.	Leaf shape and the presence of leaf hairs	Particulate matter (roadside)	Lanceolate shaped leaves accumulate more PM than obovate and elliptic shaped leaves. Additionally, leaf hairs capture more PM by increasing surface area and inhibiting their resuspension in air	Leonard *et al.,* (2016)
8.	Leaf wax	Particulate matter (diameter 2.5-10 µm)	PM immobilised by epicuticular waxes and phytostabilised inhibiting its resuspension	Popek *et al.,* (2013)
9.	High Leaf Area Index (LAI) and Leaf rigidity	Particular matter (near railway station)	High LAI implies high surface area of leaf and high number of leaves arranged in a unit area which is one of the significant traits helping in PM capture.	Weerakkody *et al.,* (2017)

in accumulating PM than leaves that are large, smooth and hairless, and covered with a thick wax layer. Hairiness and roughness are the most influential leaf traits. They further suggest that evergreen conifers with needle leaves are more effective in PM accumulation than broadleaved trees due to their thicker epicuticular wax layer, complex foliage structure, and the potential for accumulating pollutants throughout the year. Moreover, those leaves which possess a relatively rough surface with deep depressions exhibit a larger contact area for particulate matter to get absorbed or adsorbed, resulting in a higher accumulation of PM (Zhang *et al.,* 2019)

Another study by Pal and others (2001) in Lucknow, India on significance of micro-morphological leaf surface characters of plants in indication and mitigation of auto-exhaust pollution carried out on eight different species of plants concluded that the presence of granular or inconspicuous wax (mostly thick layer), smooth cuticle, and sunken stomata equip the plants better in order to face the brunt of automobile pollution. They found that though the epicuticular wax lost its shape, epidermal cells collapsed and the cell boundaries fused irregularly along with a two-fold increase in stomatal frequency and trichome length, the phenology of these plants remained unaffected by auto exhaust pollution. The investigated species though manifesting above changes remained normal and healthy and, therefore, they recommended growing of the investigated species *(Asparagus racemosus, Azadirachta indica, Bougainvillea spectabilis, Cassia fistula, Ficus religiosa, Nerium indicum, Polyalthia longifolia* and *Thevetia neriifolia)* along roadsides in areas polluted by automobile emissions.

Trees also remove a considerable percentage of gaseous air pollutants primarily by uptake via leaf stomata, though the plant surface removes some gases. Most of the gaseous pollutants in the form of O_3, SO_2 and NO_2, are removed via leaf stomata. Once inside the leaf, these gases diffuse into intercellular spaces and may be absorbed by water films to form acids or react with inner-leaf surfaces (Zhang *et al.,* 2020). Plants can also absorb formaldehyde and aromatic compounds (such as benzene, toluene, and xylene) through stomata on leaves which can be converted to phenol or pyrocatechol and subsequently to microbial acid and fumaric acid for the remediation of air pollution (Omasa *et al.,* 2002). Surface waxes and compositions also exhibit some capacity to retain and strengthen PMs. The trichome and hair density is also directly proportional to the amount of $PM_{2.5}$ accumulated on leaves (Han *et al.,* 2022).

Urban trees can capture a portion of local automobile exhaust emissions from the air depending on their positioning and planting density (Uni and Katra, 2017). These trees are also known to act as a physical barrier to the movement of pollution, similar to a wall or other physical barrier (Mori *et al.,* 2018). Kończak *et al.,* (2021) elucidated a noteworthy mitigation potential of some species of vines (*Parthenocissus quinquefolia*), shrubs (*Forsythia intermediata*) and coniferous trees, such as *Betula pendula* 'Youngii', *Quercus rubra, Cratageus monogyna, Acer pseduoplatanus, Tilia cordata* Mill. or *Platanus orientalis*. Though most of these species turned out to be the most efficient in the process of phylloremediation, *Betula pendula* 'Youngii' and *Parthenocissus quiquefolia* exhibited the greatest efficiency in collecting the highest amounts of PM in waxes. Singh *et al.,* (2022) have concluded that physiological and biophysical response of potential plant species for coping and adapting to the urban roadside environmental stresses should be considered while choosing plantation species.

Though creating green infrastructure and planting more trees goes a long way in mitigating air borne pollutants, it is also to be considered that most plants respond differently to air pollution and are hence considered sensitive, tolerant, and hardy towards air pollution depending on their ability to sustain and perpetuate in given conditions. Life cycle and interactions of plants with the environment also depends on this nature. Therefore, with the categorization of the plants, whether sensitive or tolerant towards the air pollution, the air pollution tolerance index (APTI) has been developed. APTI is calculated using four biochemical parameters like ascorbic acid content, chlorophyll content, leaf extract pH, and relative water content of leaves of plants (Bharti *et al.,* 2018). Ascorbic acid is a strong reductant and activates many physiological and defence mechanisms. Its reducing power is directly proportional to its concentration. However, it's reducing activity is pH dependent, being more at higher pH levels. Chlorophyll, on the other hand is an index of productivity of a plant. Relative water content in a plant body is important in maintaining its physiological balance under conditions of stress created by air pollution. In summary, plant adaptation to changing environmental factors involves both short-term physiological responses and long-term physiological, structural and morphological modifications. These changes help plants minimize stress and maximize use of internal and external resources. The APTI has been shown to be useful tool for selecting appropriate plant species for urban forests (Rai *et al.,* 2013; Pandey *et al.,* 2015) and crops (Malav *et al.,* 2022). Plants with higher index value are more tolerant to air pollution and can act as a sink to mitigate pollution compared to plants with low index value. Further, sensitive plant species can be conveniently used as biological indicators for air pollutants. It is critical to increasing green cover in cities by choosing plant species that are tolerant to pollution owing to their evergreen nature, large leaf surface area and appropriate leaf characteristics.

Diener and Mudu (2021) suggest that it is imperative to also take into consideration the effect of ventilation and other (micro) climatic factors on air pollution that can enhance or impede the air quality amelioration effect of green spaces. Since the urban PM concentration peaks are strongly associated with tropospheric temperature inversions, it is important to ponder carefully the interactions between green spaces' PM mitigation abilities with ground-level air temperatures, pressure, and humidity.

India is trying to accelerate economic growth and relax environmental laws, and there is tremendous pressure to divert natural systems to other uses. Hence, there is a pressing need to undertake the natural capital accounting and valuation of the ecosystem services as well, especially considering the intangible benefits provided by ecosystems in India (Ramachandra *et al.,* 2022). In wake of the current situation, it is important to create awareness about the potential of trees in sustainable development. Planting more trees will benefit society and ensure sustainability owing to the ability of trees to mitigate ambient air pollution.

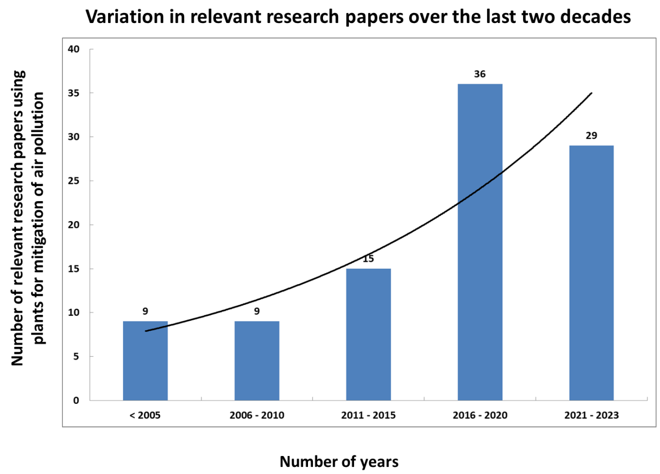

Fig. 1: Rise in the number of relevant research papers over the last two decades pointing at the importance of planting trees for mitigation of ambient air pollution

In India, a positive step towards environmental protection came in January 2019, with the Ministry of Environment, Forest, and Climate Change (MoEFCC) launching the National Clean Air Programme (NCAP) to prepare a clean air action plan. The primary objective was to reduce $PM_{2.5}$ pollution by 20-30% by 2024, compared to 2017, in 122 cities (MOEFCC, 2019). A proposal was prepared by the Ministry of Health and Family Welfare (MOHFW), for an exposure-centric management approach for integrating the health impacts of air pollution into the policy dialogue in India (Ganguly *et al.,* 2020). A clean air plan is a collection of regulations, policies, and programmes, which aims to improve air quality and public health by identifying cost-effective measures to reduce emissions from all the known sources. Central Pollution Control Board (CPCB) has implemented the National Air Quality Monitoring Programme (NAMP) which monitors and analyses air pollutants like PM_{10}, $PM_{2.5}$, Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2) Carbon monoxide (CO), Ammonia (NH_3), Lead (Pb), Ozone(O_3), Benzene (C_6H_6), Benzo(a)pyrene (BaP), Arsenic (As) and Nickel (Ni) throughout in India (CPCB, 2012). Govindarajulu (2014), put forward establishment of comprehensive guidelines for urban planners and foresters, emphasizing green space planning through integrated approaches that effectively address both the social and ecological requirements of cities.

The current study encompasses results compiled from around 100 references. It is pertinent to note that the importance of using plants as a mitigator of ambient air pollution has gradually assumed greater importance over the last two decades. The results are summarized in Fig. 1 and the exponential trendline shown there indicates more and more usage of plants for mitigation and the same has garnered enhanced interest in the last three years.

Conclusion

Health is a state-level matter in India, and the responsibility of implementing national action plans such as the National Clean Air Programme rests with the central government of India. Whether the policies are implemented or not, the potential of green plants to mitigate pollutants in the air remains unmatched. A timely policy input on setting mandatory urban green space norms and guidelines to plan environmentally and socially sustainable urban green spaces by incorporating criteria such as accessibility and availability per capita, and scientific principles such as landscape ecology, are expected to go a long way in developing urban green spaces. Generating awareness at all levels of society for a better and healthy lifestyle by breathing pure air is the need of the hour. Various studies have documented the ability of trees to absorb/adsorb pollutants. Current situation necessitates educating all about the benefits of green plants in improving public health as their potential to mitigate pollutants remains unparalleled. Investigations must be triggered to identify the native tree/shrub species which can be used for the purpose of phylloremediation as a sustainable solution to mitigate air pollution can be achieved.

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Author Contribution

Conceptualization, C.K.G; Literature review, C.K.G and N.J; Writing—original draft preparation, C.K.G and N.J.; Writing—review and editing, A.C. and Y.M. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Not applicable

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