# Evaluating and Addressing the Impact of Particulate Matter and Artificial Light At Night as Stressors On Plant Physiology And The Urban Ecosystem

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# Evaluating and Addressing the Impact of Particulate Matter and Artificial Light At Night as Stressors On Plant Physiology And The Urban Ecosystem

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## Summary

Urban Green Infrastructure (UGI) is critical to developing more resilient cities. To accomplish this, it is essential to minimize stressors on plant physiology. Particulate Matter (PM) and Artificial Light at Night (ALAN) are two important urban stressors which have a major impact on urban plant physiology including photosynthesis, growth, circadian rhythms, amino acid flow and genetics. It also studies the adaptive mechanisms adopted by plants to tackle these stressors, most prominently ascorbic acid production and highlights the unintended consequences of such strategies on plant-insect interactions and the urban ecosystem. This paper finds that in the long run these urban stressors affect plant evolution and decrease biodiversity making our urban ecosystems more vulnerable. This paper quantifies the social and economic costs these urban stressors cost to cities like Mumbai and suggests technological, social and legislative solutions to address these challenges.

## Section 1: Importance of Urban Plants

Cities have a large environmental footprint, and they have become more vulnerable to climate change. Over 55% of the world's population lives in urban areas, which is projected to reach 68% by 2050 (United Nations, 2018). Cities occupy 3% of the Earth's land surface but contribute to 75% of total anthropogenic carbon emissions and 60-80% of human energy consumption (United Nations Convention to Combat Desertification, 2020). Urban populations are more vulnerable to waterlogging, water scarcity, soil erosion and low biodiversity due to climate change and human activities. This has severe financial and social implications: for example, urban infrastructure can suffer critical damage due to cyclones, flooding or landslides. The UN Sustainable Development Goal 11 – Sustainable Cities and Communities – aims to make cities more resilient and sustainable to address the realities of climate change (United Nations, 2023).

Green Infrastructure (GI) help develops more resilient, sustainable and healthier cities and so can play a key role in achieving the SDG 11. GI is composed of natural strategically placed assets. According to Francini *et al.* (2022), GI helps in watershed management, crop cultivation, recreation and mitigation of the environmental challenge including pollution, the urban heat island effect, climate change, and reduced biodiversity. Land or waterbodies polluted by landfill leachate, industrial heavy metals or agricultural nutrient pollution are restored and remediated by plants through: Rhizofiltration, Phytostabilization, Phytovolatilization and Phytoextraction (Sleegers, 2010). GI has been linked to positive health benefits: obesity reduction, cardiovascular and respiratory health improvement. GI alleviates psychological stress, fosters a sense of community and is linked with decrease in crime levels, improved social cohesion and pro-social behavior (McKinney & VerBerkmoes, 2020). It is important to maximize the effectiveness of GI to achieve maximum benefits.


***Fig. 1****: This figure summarises the importance of Urban Green Infrastructure (UGI) and the critical role it plays in helping us achieve multiple UN Sustainable Development Goals. The figure is from* ***Herath P, Bai X****.* ***2024****. Benefits and co-benefits of urban green infrastructure for sustainable cities: six current and emerging themes. Sustainability Science* ***19****: 1039–1063.*



The paper investigates the impacts of urban stressors and focuses on Particulate Matter (PM) and Artificial Light at Night (ALAN)'s impacts on urban plants. First, the paper reviews existing literature to demonstrate the exact impact of these stressors on plant physiology, the adaptive strategy adopted by plants and the overall impact of the stressors on the urban ecosystem. The paper concludes by taking a case study of Mumbai and it suggests multiple measures to civic authorities to mitigate the impact of urban stress on plants and quantifies the cost of inaction on green infrastructure.

## Section 2: Overview of the Impacts of Urban Stressors

This section evaluates the impact of stressors induced by urbanization on plants and reviews the large impacts of urban stress on plant evolution, biodiversity and the urban ecosystem.

Urbanization has a significant impact on plant physiology evidenced by the variation in multiple traits ranging from height to dispersal strategy across the rural-urban gradient. Each stressor affects plant traits differently and hence multiple stress interactions can yield unpredictable results. (Williams *et al.*, 2015). For example, plant phenotypes with red leaves dominate plant populations in cities while in rural areas green leaf phenotypes outnumber the red (Fukano *et al.*, 2023). It is thought that red leaves are an adaptive response to rising temperature. Red leaves have an increased amount of anthocyanin which is a protective pigment and reduces damage from Reactive Oxygen Species (ROS). The paper also found significant genetic differences between the green leaf and red leaf phenotypes. The authors suggest that natural selection may act differently across the rural-urban gradient. However, the paper did not account for the potential overplanting of red leafed plants in urban areas for aesthetic reasons. Nevertheless, the experiments suggest a correlation between higher temperatures and distribution of the red leaves phenotype. A similar result was observed in the white clover which has differentiated itself across the rural and urban gradient based on hydrogen cyanide (HCN) production where urban white clovers produce significantly lesser HCN as compared to rural white clovers (Santangelo *et al.*, 2022). It is speculated that this parallel evolution has occurred over 160 cities studied to combat the low groundwater supply in cities.

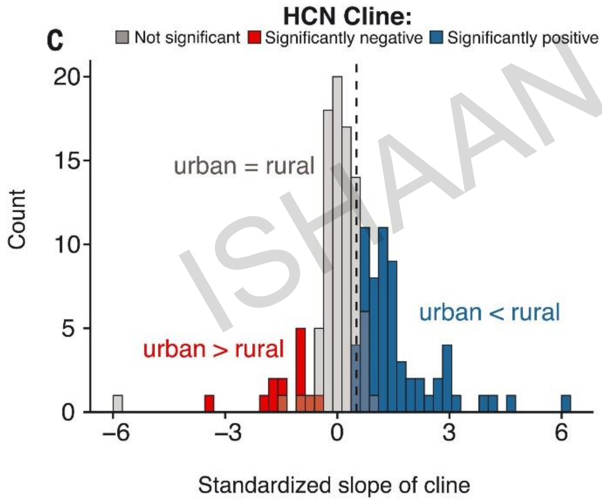



***Fig. 2:*** *This graph is from* ***Santangelo JS, Ness RW, Cohan B, Fitzpatrick CR, Innes SG, Koch S, Miles LS, Munim S, Peres-Neto PR, Prashad C, et al. 2022****. Global urban environmental change drives adaptation in white clover. Science* ***375****: 1275–1281. It graphically shows the data found by the researchers who found significantly negative production of HCN closer to the city centre as compared to rural or sub-urban areas.*

These changes induced by urban stressors are likely to fundamentally change animal-plant interactions influencing the food web, pollination and the entire ecosystem in cities. Additionally urban stressors add to selection pressures acting on plants restricting the optimum range of a trait more than rural areas.

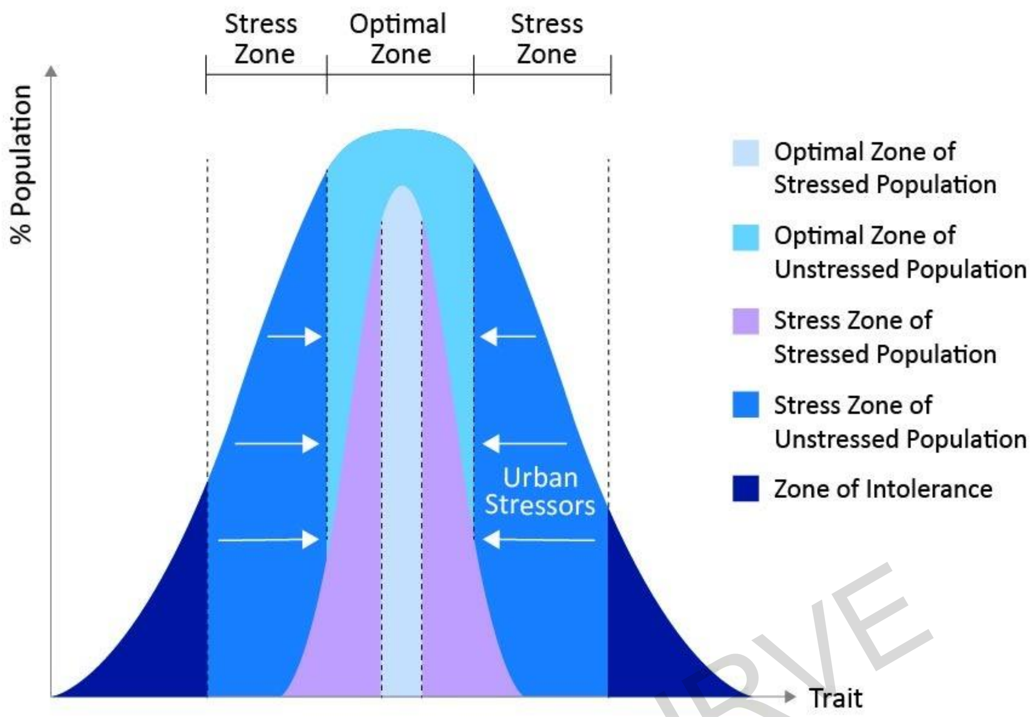



***Fig. 3:*** *Illustrates that urban stressors restrict the phenotypical diversity by reducing the optimum zone and zones of tolerance for traits. The reduction in scope of variations in the long run reduces genetic biodiversity yielding more vulnerable ecosystems.*



This reduces plant biodiversity (Williams *et al.*, 2015). The reduction of biodiversity affects the entire ecosystem and the resilience of GI. It makes plants more susceptible to pests, pathogens, climate change and invasive species. Regardless of the cause, a reduction of biodiversity decreased the ecosystem's stability and the effectiveness of its services (Hautier *et al.,*2015). Therefore, urban stressors could directly affect the biodiversity and effectiveness of green infrastructure in cities.

## Section 3: Impact of Particulate Matter (PM) Stress on Plant Physiology

This section examines the impact of PM on plants. It highlights the adaptive mechanism adopted by urban plants to combat PM stress and evaluates the unintended impacts of this mechanism on plant-insect interactions and the urban ecosystem.

Particulate Matter is a common air pollutant consisting of microscopic solid particles. It is primarily released from construction activity and vehicular emissions (United States Environmental Protection Agency, 2016). Particulate matter indirectly also pollutes the soil and waterbodies they eventually settles down on the topsoil layer (Soriano *et al.*, 2012).

Particulate Matter is a key stressor for plants which affects photosynthesis and amino acid production (Iqbal *et al.*, 2014). Exposure to PM reduces the biomass yield from photosynthesis as PM clogs the stomata and changes the leaf's optical properties by masking the leave surface thus affecting gas exchange and light absorption. Additionally, PM stress decreases the content of certain amino acids. For example, the concentration of glutamate and aspartate decreased significantly, because these compounds are utilized to detoxify the heavy metals of PM entering the plant (Pavlík *et al.*, 2012). The reduction in glutamate and aspartate levels reduces the cytokinin, chlorophyll and ATP production in plants.

| Treatment | $C_i$ (vpm) | $P_N$ (μmol $CO_2$ $m^{-2}$ $s^{-1}$) | $g_s$ (mol $m^{-2}$ $s^{-1}$) | $E$ (mmol $H_2O$ $m^{-2}$ $s^{-1}$) | WUE |
|---|---|---|---|---|---|
| 1—Control | $336.82 \pm 9.56$ | $11.31 \pm 1.25$ | $0.92 \pm 0.26$ | $3.04 \pm 0.64$ | 3.72 |
| 2—PM soil | $346.22 \pm 12.43$ | $7.46 \pm 1.05$ | $0.61 \pm 0.08$ | $3.78 \pm 0.32$ | 0.16 |
| 3—PM plant | $387.46 \pm 12.71$ | $2.75 \pm 1.44$ | $0.26 \pm 0.14$ | $5.73 \pm 0.89$ | 0.05 |

***Fig. 4:*** *This table is taken from* ***Pavlík M, Pavlíková D, Zemanová V, Hnilička F, Urbanová V, Száková J*** *.* ***2012*** *. Trace elements present in airborne particulate matter—Stressors of plant metabolism. Ecotoxicology and Environmental Safety* ***79*** *: 101–107. It summarises the experimental results of their study and the significant impacts of air pollutant PM and PM soil contamination on the stomatal conductance, the net photosynthesis rate and water use efficiency*

| Amino acid ($\mu mol\ kg^{-1}$) | Treatments | | |
|---|---|---|---|
| | 1—Control | 2—PM soil | 3—PM plant |
| Glu | $2430 \pm 42$ | $1608 \pm 28$ | $589 \pm 21$ |
| Asp | $2566 \pm 58$ | $1178 \pm 32$ | $571 \pm 19$ |
| Asn | $35.8 \pm 2.8$ | $71.0 \pm 1.9$ | $142 \pm 10.9$ |
| Pro | $98.4 \pm 11.6$ | $223 \pm 48$ | $123 \pm 17$ |
| Ala | $302 \pm 36$ | $294 \pm 32$ | $264 \pm 36$ |
| Phe | $52.3 \pm 10.6$ | $33.0 \pm 9.8$ | $31.3 \pm 4.9$ |
| Trp | $11.3 \pm 2.6$ | $20.1 \pm 5.3$ | $29.7 \pm 4.9$ |
| Gly | $33.4 \pm 6.7$ | $30.0 \pm 7.9$ | $28.8 \pm 5.9$ |
| Val | [a] | $37.1 \pm 14.1$ | $51.2 \pm 10.9$ |
| Leu | $34.8 \pm 6.1$ | $27.7 \pm 3.7$ | $39.4 \pm 4.6$ |
| Ile | $28.7 \pm 4.1$ | $24.7 \pm 5.2$ | $28.2 \pm 1.7$ |
| Thr | [a] | $163 \pm 17$ | $157 \pm 21$ |
| Se | [a] | $387 \pm 21$ | $361 \pm 19$ |

[a] Concentrations of free amino acids were below detection limit of GC.

***Fig. 5:*** *This table is taken from* ***Pavlík M, Pavlíková D, Zemanová V, Hnilička F, Urbanová V, Száková J***. ***2012***. *Trace elements present in airborne particulate matter—Stressors of plant metabolism. Ecotoxicology and Environmental Safety* ***79***: *101–107. It summarises the impact of PM on amino acid production in plants particularly glutamate and aspartate.*

Urban plants have adopted the production of ascorbic acid (AA) as a prominent adaptation strategy against high PM stress. Ascorbic acid is a major plant metabolite involved in the cell cycle, photosynthesis and antioxidation. Several studies have shown that plants upregulate the production of ascorbic acid during moments of stress (Viviani *et al.*, 2021, Alayafi, 2019, Khan *et al.*, 2011). Singh *et al.* (2020) examined the impact of PM on AA concentrations. They studied the response of five plant species along a PM gradient and found significant variation in AA response across species. All plants observed a decrease in photosynthesis and leaf pH levels, but species with the maximum AA concentration were least affected. The authors suggested that AA helped reduce the oxidative stress induced by PM on the plant. Experimental research concluded that even the artificial application of ascorbic acid helps reduce the impact of PM stress (Mina *et al.*, 2021). Further research is required to support this hypothesis and generalize it for a wider variety of plants.

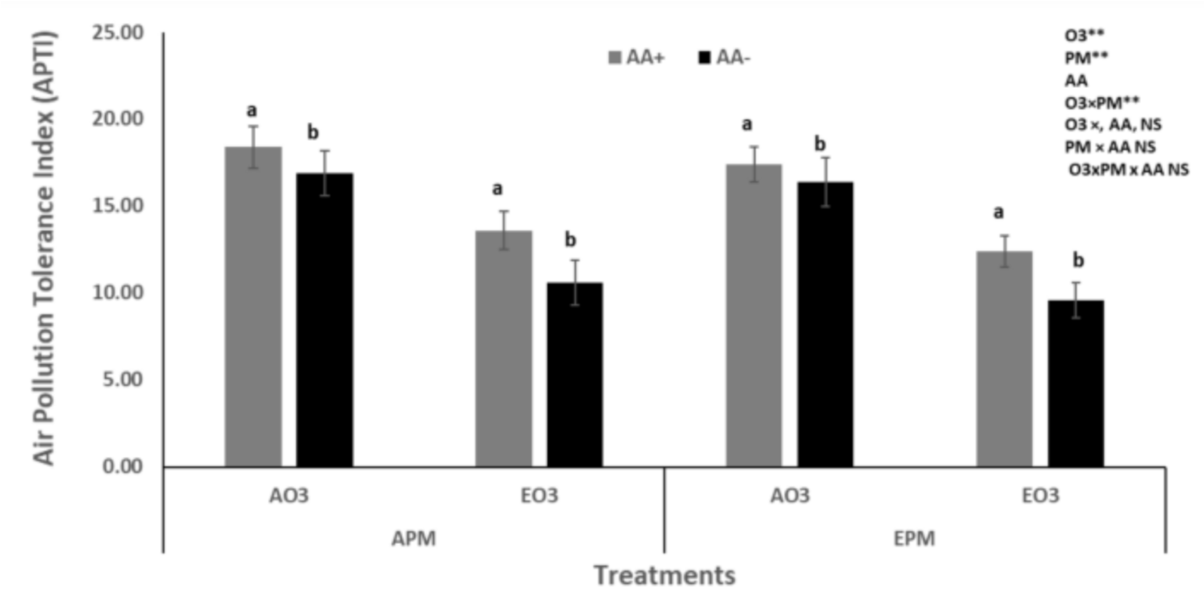



**Fig. 6:** *This figure is taken from* ***Mina U, Kandpal A, Bhatia A, Ghude S, Bisht DS, Kumar P****.* ***2021****. Wheat Cultivar Growth, Biochemical, Physiological and Yield Attributes Response to Combined Exposure to Tropospheric Ozone, Particulate Matter Deposition and Ascorbic Acid Application. Bulletin of Environmental Contamination and Toxicology* ***107****: 938–945. The graph summarises the experimental results which demonstrate that AA applied on the leaf surface improved the air pollution tolerance of plants significantly even in elevated ozone and PM levels commonly found in cities.*



However, this strategy is associated with physiological costs. Ascorbic acid is commonly produced by plants from glucose through a 10-step process – called the Smirnoff-Wheeler Pathway. The process involves multiple enzymes, redox reactions and consumes ATP (Wheeler et al., 1998). Hence, the manufacturing process of ascorbic acid affects the production of other primary metabolites and diverts carbon and energy resources away from other essential functions like growth and reproduction (Foyer & Noctor, 2011; Gallie, 2012). In optimum conditions, the trade-offs involved in are balanced, however, under highly stressful conditions it adversely affects the plant.

The excess production of AA by plants in response to PM stress also influences insect-plant interactions. Ascorbic acid plays different roles in plant-insect interactions. It is an important nutrient for herbivorous insects which regulates insect growth and reproduction (Kramer & Seib, 1982) but it is also a part of the defensive mechanism against insect herbivory, where under herbivory the ascorbic acid is oxidized to produce ROS and Dehydroascorbic acid (DHA) which disrupts the insect's cell membranes and digestion (Goggin *et al.*, 2010). Insect species follow these strategies against phytotoxins like DHA each with an associated time or energy cost: avoidance; excretion, metabolic resistance or mutated resistance (Després *et al.*, 2007). Ascorbic acid cannot be independently synthesized by insects so they are completely dependent on plants for their AA intake hence increased AA levels due to PM stress would increase the dietary consumption of ascorbic acid which would have different impacts on insects. Excess ascorbic acid could make insects more susceptible to natural predators because excess ascorbate inhibits the action of phenol oxidase which facilitates healing and provides immunity from pathogen (Goggin *et al.*, 2010). Therefore, an increase in AA levels in plants would have an unpredictable impact on insect populations which are important in cities because they: are the base of the urban food web, enable pollination, support waste decomposition and nutrient cycling (Verma *et al.*, 2023).

| Order | Species | Family | AsA range tested | Optimum AsA | Symptoms of Deficiency | Symptoms of excess | Citations |
|---|---|---|---|---|---|---|---|
| Diptera | Malaysian fruit fly (*Bactrocera latifrons*) | Tephritidae | 0–2.5%[a] | 0.5%[a] | Slower development, decreased pupal recovery, reduced overall growth index | Slower development, decreased pupal recovery, reduced overall growth index | [75] |
| Coleoptera | Cowpea weevil (*Callosobruchus maculates*) | Bruchidae | 0.002–4.4% | 0.02% | Decreased life span | Decreased life span | [11, 76] |
| | Black twig borer (*Xyleborus ferrugineus*) | Scolytidae | 0–0.5% | 0% | No adverse effect | Reduced or no reproduction, and lower female/male ratio among progeny | [77] |
| | Sawtoothed grain beetle (*Oryzaephilus surinamensis*) | Silvanidae | 0 and 0.25% | n.d. | n.d. | Slower development and higher mortality | [78] |
| Hemiptera (Heteroptera) | Sunn pest (*Eurygaster integriceps*) | Scutelleridae | 0–0.7% | 0.4% | Reduced fecundity and life span | Slower development | [79] |
| | Striped shield bug (*Graphosoma lineatum*) | Pentatomidae | 0–0.3% | n.d. | No adverse effect | Lower fecundity, egg viability, and life span | [79] |
| Hemiptera (Homoptera) | Green peach aphid (*Myzus persicae*) | Aphididae | 0–0.8% | 0.2% | Lower weight | Lower weight, higher mortality | [28, 34] |
| Lepidoptera | Codling moth (*Cydia pomonella*) | Tortricidae | 0.1–1% | 0.6–0.8% | Higher susceptibility to bacterial and fungal infections | Higher susceptibility to bacterial and fungal infections | [12] |
| | Oriental leafworm (*Spodoptera litura*) | Noctuidae | 0–1% | 0.5% | Slower growth and high mortality | Slower growth and high mortality | [27] |
| | Cabbage looper (*Trichoplusia ni*) | Noctuidae | 0–0.75% | 0.5% | Death, wing deformity | Wing deformity | [31] |



***Fig. 7:*** *The table is taken from* ***Goggin FL, Avila CA, Lorence A*** *.* ***2010****. Vitamin C content in plants is modified by insects and influences susceptibility to herbivory. BioEssays* ***32****: 777–790. It provides information about how changes in dietary ascorbic acid level would affect different insect species. It is evident that an increase in AA concentration would cause unfavorable conditions like deformity, higher mortality or reproductional abnormalities.*

At the same time Abdu-Allah *et al.* (2020) linked the dietary consumption of AA to resistance to chemical pesticides like dichlorodiphenyltrichloroethane (DDT) in insects. This was likely due to AA's strong antioxidant properties which protects the insects from the oxidant molecules produced by DDT therefore due to the increased dietary consumption of AA insects the efficiency of the conventional pest control methods of civic authorities involved in health and sanitation would decrease. Further research is essential to understand how AA impacts insect populations in urban environments.

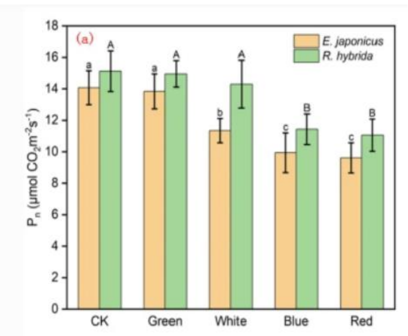
## Section 4: Impact of Artificial Light at Night (ALAN) Stress on Plant Physiology

This section explains the sources of ALAN and derives the relationship between PM and ALAN in urban areas. It reviews scientific literature to demonstrate the impact of ALAN on plant physiology – photosynthesis, growth and circadian rhythms. It links the phenomenon of phenology mismatch with ALAN stress and elaborates on the impact of ALAN on animal-plant interactions affecting the entire urban ecosystem, biodiversity and evolution.

Artificial Lights at Night are used for – streetlamps, bridge lighting, aircraft warning lights or landscape lighting found in public squares, parks or monuments in cities. According to (Falchi et al, 2016) 80% of the world population is exposed to light polluted sky and globally since 2011 light pollution has increased by 10% each year. The range of impact of artificial light is multiplied by sky glow. Skyglow is the artificial brightening of the night sky because of scattering of artificial light from particulates in the atmosphere hence it is positively correlated with air PM concentration (Guo *et al.,* 2023).

Artificial Light at Night affects plant physiology by inducing oxidative stress on the plant which affects the chlorophyll A, chlorophyll B and carotenoids content and hence the net photosynthesis rate. Despite the reduction of daytime photosynthesis rate, the net carbon produced is greater due to supplemental food production at night. The additional carbon produced is invested in growing longer branches in the trees. However, by stimulating photosynthesis at night ALAN also disrupts the dark respiration phase in plants (Wei *et al.*, 2023). Prolonged ALAN exposure affects the plant stomata, because exposure to ALAN stimulates the opening of the stomata throughout the night facilitating gaseous exchange. The sustained stomatal opening in the long-term causes dysfunctional movement and starch degradation in the guard cells which affects transpiration and gaseous exchange and photosynthesis in the daytime (Piccolo *et al.*, 2024). On analyzing the RNA of the experimental plants, Piccolo *et al.* (2024) found that stress signaling, hormone regulation, maintenance of redox systems and regulation of ion transport was also affected by ALAN exposure since over 1424 genes were significantly differently expressed.

***Fig. 8:*** *This graph was taken from* ***Wei Y, Li Z, Zhang J, Huang D*****.** ***2023****. Influence of night-time light pollution on the photosynthesis and physiological characteristics of the urban plants Euonymus japonicus and Rosa hybrida. Ecological processes* ***12****. It demonstrates the effect of ALAN stress across the different light spectrums and species on the net photosynthesis rate*.




Artificial Light at Night triggers multiple changes in a plant's circadian rhythms and life cycle which affect the entire ecosystem. Prolonged exposure to artificial light leads to the retention of leaves beyond winter and changes leaf coloration patterns. Artificial Light at Night severely affects the flowering patterns of plants dependent on photoperiodism. Artificial Light at Night also alters the flowering phenology by over 4-12 days depending on the spectrum and light intensity (Hufnagel, 2022, pp. 18). This can result in phenology mismatch in the ecosystem, for example, ALAN causes the mismatch between moth hatching and spring budburst of trees which reduces the moth population and has irreversible unknown effects on the ecosystem (BOYES *et al.*, 2020). ALAN is disruptive to many plant-animal interactions like herbivory, pollination, and seed dispersal. For example, visits by nocturnal pollinators to plants in ALAN areas decreased by over 62% (Hufnagel (2022, pp. 19).


***Fig. 9:*** *The image shows the impact of ALAN on leaf retention in a deciduous tree in London. The tree with leaves receives high exposure to ALAN hence, there is no autumn coloration and leaf retention into the winter. The figure is taken from* ***Bennie J, Davies TW, Cruse D, Gaston KJ****.* ***2016****. Ecological effects of artificial light at night on wild plants (N Swenson, Ed.). Journal of Ecology* ***104****: 611–620.*

However, the impacts of ALAN are not universal. Experimental research by Wei et al. 2023 has concluded that the effects of ALAN on plant physiology depend on the ALAN spectrum and intensity. Additionally, different plant species are differently affected by ALAN stress suggesting that unknown adaptive mechanisms may have been evolved by plants to adapt to ALAN. So, ALAN may be a subtle driver of evolution which adds selection pressure to multiple traits resulting in differences in individuals of the same plant species across the rural-urban gradient (Hopkins *et al.*, 2018). ALAN also affects the flow of genetic material by disrupting the lifecycles of pollinators. It could limit the dispersal of plant genetic matter in the urban area resulting in overcrowding and limited genetic diversity. Work done by Bucher *et al.* (2023) supports his hypothesis, the paper found that when a grassland community was exposed to ALAN stress while species richness remained constant the Shannon diversity index which considers species richness, and their populations' relative abundances (evenness) decreased by over 43%. This indicates that the overall genetic diversity of a community decreased significantly due to ALAN exposure.

## Section 5: Case Study - Minimizing Adverse Impacts of PM and ALAN Stress on Plants in Mumbai

This section evaluates the impact of PM and ALAN urban stressors on Mumbai's urban ecosystem. It quantifies the economic and social cost of these stressors on civic authorities and suggests multiple measures that authorities can adopt to mitigate these stressors and create a more resilient GI.

Mumbai is the financial capital of India, the $6^{th}$ most populated metropolitan city in the world with over 23 million inhabitants. The city is highly vulnerable to climate change. It is predicted that the city could lose 10% of its area by 2040 and by 2070 over 11 million people would be displaced due to rising sea levels. It has a high carbon footprint of over 23.42 million tons of CO2 (Ministry of External Affairs, India, 2022). Mumbai possesses multiple industrial areas which produce textiles, petrochemicals, automobiles and electronics including Trans Thane Creek MIDC, MIDC Industrial Zone and Industrial clusters in Andheri, Vasai, Goregaon and more. It has become infamous for its extreme irregular rainfall, cloudbursts and tsunamis and other extreme weather events projected to continue rising due to climate change. These disasters disrupt regular life and devastate the city's economy. For instance, in the July 2005 deluge, Mumbai experienced heavy flooding resulting in over 3-5 billion USD of financial loss and over 500 fatalities (Ranger *et al.*, 2010).

Green Infrastructure plays a critical role in reducing the city's carbon footprint, improving Mumbai's resilience to climate change and in the city's transition to a greener and more sustainable developmental model. Green Infrastructure phytoremediate the soil and water pollution caused by Mumbai's Industries which release heavy metals. It helps bind the soil together, improve percolation of rainwater and protects the coastal city from Tsunamis hence GI will be an asset for Mumbai's adaptation to a changed more extreme climate. GI also provides multiple positive health and wellness benefits to the citizens of Mumbai. However, the effectiveness of Mumbai's GI is compromised by the influence of urban stressors and unsustainable anthropogenic activities.

A prominent stressor for the GI in Mumbai is PM which has been discussed in section three. The city suffers from heavy air pollution due to high construction activity and vehicular emissions. Mumbai is home to over 4,600,000 vehicle (Rao, 2024) and many parts of Mumbai including Ghatkopar, Bandra, Bhandup, Dombivli and more are undergoing redevelopment where the original building structure is demolished, and a new edifice created to accommodate the larger population. In addition, multiple infrastructural projects being constructed simultaneously throughout the entire city adding PM to the atmosphere for instance the metro project alone is responsible for 3.2% of the total PM emissions (Brihanmumbai Municipal Corporation *et al.*, 2022). A collaborative study with IIT Bombay and NEERI concluded that 70% of PM load is caused due to road maintenance and construction (Devasia, 2023). In 2023 Mumbai has the second worst air quality in the world. This problem is going to exacerbate further as the Brihanmumbai Municipal Corporation (BMC) has given a record 2500 building approvals while 4,500,000 construction projects are continuing. Environmentalists have observed on the field the adverse impacts of PM in Mumbai. This data has been collected through personal interactions with environmentalists – Mr. Stalin Dayanand (Vanashakti), Mr. Nandakumar Pawar (Sagarshakti), Mr. Amar Deshpande (Sustainability Officer at Godrej & Boyce); builder Mr. Jayesh Shah (Damji Shamji Shah Group), Mr. Jay Gajra (J.V.G Constructions), Mr. Ankur Shah (Shapoorji Pallonji) and Mrs. Rakhi Jadhav (Corporator of N Ward, BMC).

Another prominent urban stressor in Mumbai (popularly known as the “city that never sleeps”) is ALAN. Urban vegetation in Mumbai faces ALAN stress from different sources, including streetlamps, decorative lighting, wedding or festive decorations, floodlights and advertising billboards. According to the Awaaz foundation in many parts of Mumbai 273 and 223 lux values (indicative of light intensity) are observed, while doctors advise that light levels above 50-60 lux are harmful to human health (Nair, 2019). This matter has recently received recognition from the Bombay High Court who issued a notice to the BMC and state government to curb the installation of decorative lights on trees. However, there is limited awareness and action being undertaken to tackle this problem.

**Fig. 10:** *A satellite picture of Mumbai from space at night taken from **Gaspar I. 2016**. Mumbai Night Lights from Space. Citylumens.com. The image highlights the artificial light pollution at night in Mumbai due to streetlamps, floodlights, decorative light and more which induces stress of Mumbai’s urban vegetation.*

The urban stress faced by the plants due to ALAN and PM has a large social and economic cost to Mumbai. Since 2012 over 24,000 tree fall incidents have been recorded, 37 people have died and 292 injured due to tree/branch fall. ALAN can cause tree branches to grow unnaturally longer which affects the overall plant stability during the torrential monsoon. The BMC annually spends INR 60,000,000 on tree trimming to address these incidents. The effect of increased ascorbic acid levels in plants in response to PM concentration would have an unpredictable impact on the ecosystem, however, as discussed in the section three it could reduce the efficiency of chemical pesticides used against insects to control the spread of diseases and to promote sanitation. The BMC currently spends over INR 18,00,00,000 only to control the spread the malaria for six months (Jain, 2010), hence the development of insect resistance would dramatically increase this cost since the BMC would have to utilize more concentrated or larger quantities of pesticides. Excessive use of these chemicals would also contaminate the soil, groundwater supply and affect non-target organisms. Under the influence of urban stressors including high light intensity or high temperature plants release volatile organic compounds (VOCs) namely green leave volatiles (GLV) (Holopainen & Gershenzon, 2010). These VOCs react with ground-level ozone in the presence of sunlight released from industries or vehicles to produce photochemical smog endangering the health of citizens. Hence, the civic authorities, namely the BMC, Maharashtra State Government and the Maharashtra Pollution Control Board (MPCB) have a strong financial and social incentive to implement measures to tackle ALAN and PM stress. Mumbai could be considered as the first site to experiment and address these issues by the government since it faces high levels of both stressors. Later this sustainable developmental model could be replicated in other major cities like Delhi, Chennai, and Bangalore as well.



Below some measures are suggested to civic authorities in Mumbai to reduce the impacts of PM and ALAN stressors on plant physiology and urban green infrastructure through legislative, policy and technological changes.

The authorities must focus on minimizing PM and ALAN pollution. In Mumbai, the construction industry is one of the largest PM sources. The MPCB and BMC have already set up regulations for construction sites to reduce PM release by misting, covering trucks carrying construction debris and constructing windbreaks around the site. However, these norms are seldom followed within the construction industry due to the absence of an effective monitoring system. The authorities can collaborate with industry and technological experts to develop a better model to tackle the PM waste. Internet of Things Technology (IoT) can be effectively leveraged to assess PM concentration levels at infrastructural and residential construction sites and automating the misting procedure. Godrej & Boyce, a prominent construction company, has constructed a zero-waste ecosystem where the misted PM collected is reused to manufacture ready to mix cement. This business model could be replicated by other construction companies as a part of their Corporate Social Responsibility and the government could incentivize the transition towards these sustainable practices by considering this while rewarding infrastructural projects. The authorities, NGOs and citizen groups must also focus on raising awareness about the negative impacts of PM on health and the environment. This can be implemented through street plays, social media and mainstream newspapers. The increase in awareness would incentivize the transition of construction businesses to the suggested more sustainable model. These steps would help reduce plant stress, improve human health and air quality dramatically. These mitigation measures can be accompanied by effectively utilizing Mumbai's GI for maximum impact.

This can be accomplished by identifying and growing species most effective in trapping PM and highly tolerant to PM stress. There are multiple foliar leaf characteristics which influence the plant's capability to trap PM stress. Different plant leaves retain different amounts of PM, experimentally it has been found that coniferous species accumulate the maximum PM deposit due to their shorter, narrower needles. Additionally, micromorphologically characteristics of leaves like groove areas and presence of trichomes (leaf hair) are positively correlated with PM capture (Chen *et al.*, 2017). Yu *et al.* (2018) developed a model that considers these leaf characteristics and predicts the impact of PM on the photosynthetic rate. This model predicts that leaves with trichomes (leaf hairs) and rougher leaves were least affected by the PM stress despite retaining higher quantities. These insights are very important and would help civic authorities identify the ideal vegetative sinks for PM. In addition, scientific experiments must be conducted to investigate whether the PM tolerance trait can be genetically transmitted down generations and whether nurseries or government authorities can develop and grow genetically modified strains which are PM tolerant.

The civic authorities must also wash the leaves of plants regularly with water to wash off the accumulated PM. The deposit must be led into the sewage system where it can be treated ensuring no water contamination. Authorities could also consider further investigating the experimental research conducted by Mina *et al.* (2021) which stated that the application of ascorbic acid on plant leaf can enhance their capability to tackle PM stress. After some experimental validation with local varieties this could be implemented in Mumbai and the overall success gauged.

To tackle ALAN stress on GI, first ALAN pollution must be mitigated. Authorities must strictly punish the misuse unnecessary light pollution often used in weddings, private functions, and festivals beyond a certain hour by enforcing financial penalties. The High Court's ruling regarding the removal of decorative lights on trees must be immediately implemented. Strict norms must be drafted limiting commercial lighting by cafes, restaurants, and malls beyond a certain time. On the national scale a law must be introduced to address this modern issue like the Indian Water Pollution (Prevention and Control) Act or the Air (Prevent and Control of Pollution) Act.
Beyond enforcement efforts must be undertaken by the Education Department to raise awareness about this modern growing issue. According to a questionnaire survey conducted by Kaushik *et al.* (2022) using convenience sampling method on an Indian population with diverse age, gender demographics over 50% had not heard or were unsure of the term 'light pollution' and 47% thought that their peers were unaware of this threat. It is important to note that the awareness was likely overrepresented due to the social desirability bias and skewed representation. Environmental Science has been introduced in most of the primary, secondary, and higher education boards in India therefore the Education Department must instruct all national educational boards to incorporate modules on ALAN and how artificial light pollution can be minimised on the individual level.

To address ALAN technological innovation can be introduced that limit physiological harm to the plants but cause minimal inconvenience to the citizens. In the experiment design ed by Wei *et al.* (2023) it was found that green light provoked the least negative response from the experimental plants and that low intensity lights triggered the least response from plants. Therefore, authorities should consider utilising low intensity, non-blue and non-red light spectrums for streetlights as well. Additionally, urban planners could consider using insights from satellite technology or artificial intelligence to optimise the placement of streetlights and other functional ALAN emitters actively weighing the impact the ALAN stress contributed has on plant physiology.

The suggested measures would reduce the impact of urban stressors on plant physiology, urban biodiversity and ecosystem. It would result in a more resilient city with a stronger urban GI which in the long run will be financially and socially beneficial to the city.

## Section 6: Conclusion

Tackling PM and ALAN stress is crucial globally in all urban environments to increase the efficiency of green infrastructure and protect urban ecosystems. Minimising stress would increase biodiversity, prevent anthropogenic induced unpredictable parallel evolution across urban areas as seen in white clover in section one and make cities more sustainable and resilient. The paper has successfully explored the impacts of PM and ALAN on plant physiology, reviewed the adaptive strategies adopted by plants to tackle the stress and investigated the unintended repercussions on evolution, the food web and urban ecology.

This paper has found multiple gaps in existing literature. More scientific study is necessary to analyse the precise role of ascorbic acid in plant-insect relations and how an increase in AA concentrations in plants would affect insect nutrition, insect's pesticide resistance and the plant herbivory defence mechanism. More research is necessary to understand the metabolic or physiological adaptive mechanisms of plants towards ALAN stress. Experimental research should be conducted over whether PM or ALAN tolerance is genetically inheritable. More detailed research about how ALAN and PM affect the urban ecosystem in Mumbai and India is essential. It would also be interesting to investigate whether ALAN and PM stressors help invasive species dominate over native plants. Answering these gaps in literature would help policymakers, environmentalists and citizens take well-informed decisions to mitigate the impacts of these urban stressors on GI.

The paper took the case study of Mumbai, to highlight the financial and social importance of ameliorating the adverse impacts of urban stressors on plant physiology. It has made multiple suggestions to the local authorities towards mitigating these stressors and supporting urban plants to adapt better from PM and ALAN by using science and technology. The implementation and exploration of these suggestions and more measures would be beneficial not just for the city of Mumbai but for cities globally each of which subject their GI to similar stressors resulting in social and economic losses.

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