The projected deposition and removal of particulate matter by
green façade drapes: a case study at SAINTGITS.

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Abstract. The hazardous sub-micron particulate matter (PM₂.⁵) that goes deep in to the respiratory system causes significant threat to the life expectancy of humans. The atmospheric wind and the diurnal dry bulb temperature are the main factors which govern the pollutant dispersion. This work quantifies the wind assisted deposition of PM₂.⁵ and the natural atmospheric cleansing by a massive green façade drape. The proposed leaf foliage covers the entire South and the West facing walls of a six storied built structure (Visvesvara Block) at SAINTGITS, a prominent Technologic al Institution at Kottayam, Kerala State, India. Whilst the south blowing winds assist the deposition of PM₂.⁵ on to the façade foliage, the removal rate of the pollutants is directly proportional to the stomata opening and the humidity. This case study clearly depicts the natural capability of green façade retrofits to cleanse the atmosphere, thus helps to attain one of the seventeen Sustainable Development Goals (SDGs) of UN.

Keyword: Sustainable, Green façade, Atmosphere cleansing, SAINTGITS, Particulate Matter.

1. Introduction
The global warming and its related catastrophic debates are one among the few issues that need immediate intervention, both at the national and international level. The Intergovernmental Panel on Climate Change (IPCC), the intergovernmental body of the United Nations to assess the science related to climate change has therefore released its Special Report on Global Warming of 1.5°C, in the month of October, last year [1,2]. Though the IPCC’s 6th Assessment Report (AR6) is due in 2022, it has updated the 2006 Guidelines for the National Greenhouse Gas Inventories through another release in May 2019. The most recent release, Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) happened on the 25th day of September 2019. These many intermittent special reports make the forthcoming AR6, the most awaited Assessment Report in the entire thirty years’ history of IPCC [3].

The toxic emissions from industries and the fossil fuel powered vehicles are a few of the major air polluting sources [4,5]. To alleviate the issues related to the latter, stringent emission norms are practiced worldwide [6]. India being one of the major consumers of fossil fuel, the government has marked their stand by enforcing Bharat Stage 6 (BS6) emission standards mandatory, right from the first day of April 2020. It is in fact a direct leap from BS4 [7]. However, the optimal vehicle emission...
performance can be achieved only if the fuel and the vehicle emission standards are implemented simultaneously [8]. In India, there is tremendous rise in the vehicular density [9]. Even after a decade since 2007, the city of Ahmedabad in the state of Gujarat (one of the oldest cities) is experiencing the nightmare of rise in vehicular registrations [9]. Whilst in 2007, the total registered vehicles were merely thirty-one thousand, it has increased tenfold in 2016 (Fig 1).

Figure 1. Year wise distribution of registered vehicles in the city of Ahmedabad, Gujrat, India.

The congested traffic systems and the extended idling at metropolises have resulted in serious health issues. The fine particulate matter (PM$_{2.5}$) spewed from the vehicular exhaust are inhaled directly into the respiratory system [10]. Technological modifications alone cannot ascertain the availability of healthy and clean air. Though sustainable initiatives gradually dilute the atmospheric pollutants, stringent policies are to be instilled to attain long term benefits.

This research quantifies the natural removal of hazardous Respirable Particulate Matter (RSPM), usually lesser than 2.5 microns, by massive living green foliage, either retrofitted or directly draped on to the walls of built structures.

2. Material and methods

The SAINTGITS group of Institution houses the trio; SAINTGITS College of Engineering (SCE), SAINTGITS Institute of Management (SIM) and SAINTGITS College of Applied Sciences (SCAS). The nearest town being Kottayam, located well inside 10km radius from SAINTGITS campus, is geographically christened as 9.59°N and 76.52°E, Kerala State, India (Fig 2). The SAINTGITS campus is architectured with immensely symmetrical constructions. With the Administrative Building (AB) as the central icon, the Ramanujam Block (RB) and Visvesvaraya Block (VB) are at the North and South respectively (Fig 3).

Figure 2. SAINTGITS Campus – located nearer the southern part of India

Figure 3. SAINTGITS Campus – architected with symmetrically built structures
This work is mainly focused on the Visvesvaraya Block (VB), a six storied built structure with a total carpet area of more than 3500m². This massive structure houses several conventional and smart class rooms, faculty cabins and seminar halls. A few laboratories too are accommodated at the ground floor. The frontage completely affords a view of the North direction, with immense open space to move around (Fig 4). At the initial stage of this work, an architectural model of VB was created in DesignBuilder (Fig 5). A few similar studies on other built structures at SAINTGITS too had the same approach [11,12].

Figure 4. Elevation of the Visvesvaraya Block, facing the North direction with ample open spaces to move around.

Figure 5. The Visvesvaraya Block (VB) 9.50°N & 76.55°E – The plan in DesignBuilder, representing the North direction.

Since the wind direction and wind speed affect the pollutant dispersion and absorption, a wind rose was plotted in WRPLOT viewer to identify the prominent wind direction. The pollutant dispersion pattern and the terrain specific pollutant concentration were studied in SCREEN viewer. The pressure drop profile at different wind speeds were modelled in ANSYS Fluent to analyze the probable removal rate of pollutants by the green drape. Earlier studies have established the capability of green drapes to cleanse the air by absorbing the atmospheric pollutants [13,14]. In this work, we project the capability of green facades, draped on the South facing rear walls of the Visvesvaraya Block, to absorb and remove the fine particulate matter (PM$_{2.5}$).

3. Results and discussions
The findings of this work are illustrated under six unique sections: (a) preparing the architectural model of the VB in DesignBuilder, (b) daylight analyses in the VB, (c) thermal comfort analyses in VB, (d) determining the wind speed and wind direction, (e) estimating the terrain specific pollutant concentration and (f) the projected pollutant absorption capability of green facades and the significance of wind speed.

3.1 Architectural model of the Visvesvaraya Block
An exclusive architectural model of the Visvesvaraya Block (VB) was recreated in DesignBuilder, an exclusive modelling and analyses software which is based on the EnergyPlus freeware to emulate daylight and occupant comfort status in built structures. The software’s robustness is vouched equally by engineers, architects and energy assessors. Though it is orally branded as a six storied building, the sixth floor has only two conventional class rooms. The remaining part serves as open terrace (Fig. 6).
Figure 6. Architectural model of the Visvesvaraya Block, created and rendered in the DesignBuilder, showcasing the open terrace at the sixth floor

Except for the ground floor, at all the other levels, the partitions are identical. The ground floor has two conventional class rooms and the remaining space is dedicated for the laboratories. For effective analyses, the entire ground floor area of 744 m$^2$ has been sub-divided into 18 thermal zones, each zone emulates the respective partition in real (Fig 7).

3.2 Daylight analyses in the Visvesvaraya Block (VB)

The energy analyses performed on the architectural model of the Visvesvaraya Block have studied two main domains where energy is usually expended in built structures – (a) the daylight analysis and (b) the cooling design.

The daylight analysis was done for three floors - the ground, first and fourth floor of the VB (Fig 8, 9 & 10). For the analyses, the daylight was measured in terms of Spatial Daylight Autonomy (sDA). The sDA indicates the percentage floor space that receives sufficient daylight. To be precise, it is the percentage of floor area that receives minimum 300 lux, at least for half of the annual occupancy hours [15].

Figure 7. Wire frame model and the axonometric view – ground level of the Visvesvaraya Block with 18 thermal zones and total area = 744m$^2$.

Figure 8. Visvesvaraya Block’s Ground floor – the partition and the annual daylighting result.
While comparing the daylighting analysis for all the floors, the results obtained are different for each floor. This is due to the difference in internal partitions and openings. Though the ground floor and the first floor have almost similar results, the ground floor has equal proportion of lighted area and darker area. The daylight varies from 0 sDA to 60 sDA - the recorded extremities being the darkest and brightest areas. The fourth and the remaining floors exhibit slight variation from the Ground floor and First floor results (Fig 8, 9 & 10).

Figure 9. Visvesvaraya Block’s First floor – the partition and the annual daylighting result.

Figure 10. Visvesvaraya Block’s Fourth floor – the partition and the annual daylighting result.

The exclusive analyses of the first and fourth floors individually revealed that the fourth floor has 12% to 15% more darker areas than the first floor (Fig 9 & 10). The regions of 0 sDA demands the mandatory need for artificial lighting. The daylighting varies from 0 – 60 sDA. The darker areas are the wash rooms and the passages. Since the faculty cabins that are present in the fourth floor have proper design of windows and ventilations, they do not need any artificial lighting. The class rooms in this floor receive sufficient daylight from the rear side windows (Fig 10).

The atrium (covered transparent opening to the sky) provides sufficient lighting to the regions around it. On generalizing the daylight analysis result of the fourth floor, the windows immensely contribute to the internal daylighting than other modes. Since the internal partitions are less, the amount of light that is spread inside the first floor is nearly 12% more than the ground and the fourth (Fig 8, 9 & 10).
The faculty cabins at the fourth floor need less artificial lighting due to presence of windows on both walls and the absence of internal partitions. The only class room present in the floor receives daylight from the rear side windows and hence, the artificial lighting required is lesser than the other rooms at the same level. Except the ground floor all the other floors receive the benefits of the atrium. On generalizing the daylight analysis results of the first floor, the open veranda provides the most amount of daylight to the floor.

To reap more benefits of the daylight, an improvised design is modelled and analyzed. The first floor’s opaque ventilations are replaced by additional windows above the lintel height - the results are promising. The suggested design has more regions that receive the daylight (Fig 11). Hence, it is recommended to change the conventional building materials at specific pockets with transparent glasses. Whilst in the case of the existing design, the received daylight inside the building varies from 0 sDA to 60 sDA, the new design receives natural lighting up to 70 sDA (Fig 11).

Figure 11. Visvesvaraya Block’s First floor – the improvised daylight obtained with altered design.

3.3 Thermal comfort analyses in the Visvesvaraya Block (VB)

The varying levels of thermal comfort at each of the floors for the entire VB was analyzed, separately for normal and extreme weather conditions. In tropical climes, since most of the energy expended is to provide cooling, the results from these analyses are more significant. The operative temperature is a direct indication of the extent of both passive cooling load and the indoor occupant comfort, the latter governed by three environmental parameters - the air temperature ($t_r$ in °C), mean radiant temperature ($t_a$ in °C) and the air speed (v in m/s) (refer equation 1) [12,16,17].

$$\text{Operative Temperature} = \frac{[t_r + t_a \sqrt{100}]}{[1 + \sqrt{100}]}$$ (1)

The diurnal variation of relative humidity for normal days was recorded along with the operative temperature, measured separately for the Ground, first and the fourth floors. The plot was obtained for every alternate hour, starting from 02:00 hrs (early morning) (Fig 12). The average relative humidity was measured as 55% with a peak of 68% at 16:00 hrs. During the active hours of the day (08:00 hrs to 18:00 hrs), the operative temperature of all the three floors plateaued in between 24°C and 26°C.

Since the built structure absorbs the sun’s heat and starts to radiate the same towards late afternoons, evenings and early night experiences higher operative temperatures. But as the built structure cools after sunset, the graph exhibits a gradual decrement after 22:00 hrs. Though the ground floor operative temperatures had similar trend as the first and fourth floors (post 18:00 hrs until 08:00 hrs), it was on the higher side by approximately 1°C – 2.5°C (Fig 12).
The fabric heat gain, especially through the walls were plotted independently for the ground, first and the fourth floors (Fig 13). Throughout the day, the values of fabric heat gain for all the floors of the built structure were same – except at 06:00 hrs and 20:00 hrs. A stark comparison with the relative humidity revealed a similarity in the trend. Whilst both the relative humidity and fabric heat gain exhibited an increasing trend from morning 08:00 hrs until late afternoons, after 18:00 hrs, both stooped at 20:00 hrs and plateaued until 06:00 hrs (Fig 13). Hence, it is clear that the fabric heat gain is directly proportional to the relative humidity and the area of the fabric.
The solar gain (fabric heat gain) is separately plotted for the summer and winter days (Fig 14). The results reveal that the average fabric heat gain is nearly 21% more during the summer than the winter days – a direct contributor to the undesirable carbon footprint [18]. It directly points to the fact that during the summer days, this built structure permits more heat transfer through the fabric. The range of value fluctuates between 15kW to 40kW on summer days and 18kW to 27kW on winter days (Fig 14).

![Figure 14. Solar gain vs. time (summer and winter days)](image)

The difference in solar gain through the exterior windows were plotted to analyze the percentage difference in solar gain during summer than the winter, keeping the values of normal days as datum (Fig 15). Whilst the difference ranges between 15 kW to 20 kW on winter days, the value is not more than 5 kW during summer days. Hence, it has been proved that the windows too play an equal role as the walls while contributing to the fabric heat gain.

![Figure 15. Solar gain vs. time](image)
Infiltration is the unexpected and uncontrolled passage of outside air into the indoor region. During winter days, the solar azimuth varies from 100° N to 250° N. The narrow band of solar azimuth variation is directly related to the external infiltration (Fig 16). It also depends on the wind speed, wind direction and the air-tightness of the building envelope. The infiltration is more, both in normal and summer days than in winter days (Fig 16). During summer, the external infiltration is directly proportional to the cooling load.

![Image](image_url)

**Figure 16.** Solar Azimuth and External Infiltration vs. time

3.4 Wind direction and wind speed at the geographical locale of the Visvesvaraya Block (VB)
The geographical locale of the Visvesvaraya Block demands an exclusive analyses of the wind pattern. Most of the atmospheric pollutants, depending upon the particulate size, are dispersed through air to various distances from the source. Hence, a wind rose was plotted using WRPLOT view, a free software, to get a scientific insight into the probable pathways through which the pollutants disperse (Fig 17)

![Image](image_url)

**Figure 17.** The wind rose showing the wind direction and speed recorded during the month of June 2019 at Kottayam, Kerala State, India.
The pre-recorded wind speed and the wind direction for all the days of June 2019 were retrieved from the database of timeanddate.com and the wind rose was generated using WRPLOT. Within the wind’s speed band of 3.6m/s and 5.7m/s, the wind is more predominant in the South – West direction (for nearly 36% of the total time). Since the wind carries the fine particulate pollutants, the rear side facade of the Visvesvaraya Block certainly receives the direct wind blow. A minimum wind speed of 2m/s and a maximum of 8.8m/s were experienced by the rear facade (Fig 17).

3.5 Terrain specific pollutant concentration (projected) near the Visvesvaraya Block (VB)
The freeware, SCREEN 4.0.1 was used to plot the terrain specific pollutant concentration. The emissions from an automobile fitted with a normal Hyundai 2.2L engine is nearly 1.3gm/km [19]. If the vehicle runs at 60km/hr, an average of 0.0216g/m of toxic emissions are spewed in every second. If 1000 such automobiles run, the total emissions will work out to be 21.6gm/s.

Assuming the velocity and temperature of the emissions as 6m/s and 77°C (350K) respectively, the concentrations of the pollutant at different distances away from the source were plotted (Fig 18). Since the position of the exhaust pipe of all the vehicles are well inside 1m from the ground level, the fine particulate matter (PM\textsubscript{2.5}) becomes airborne and rises for every increase in horizontal distance from the source (Fig 18).
As the emission temperature reached 500°C, the pollutant concentration exhibited a rise at 50m (approximately 150µg/m³ more than at 350°C). At 100m away from the pollutant source, whilst the pollutant concentration at 350°C exit temperature is 525µg/m³, at 500°C it reached above 1200µg/m³ (Fig. 19). A similar increase is vivid at all the intermittent distances. Hence, it is inferred that at higher exit temperatures, the pollutant concentration surges (Fig 18 & 19).

3.6 Pollutant absorption capability of green facades and the significance of wind speed

The green vegetation can improve the air quality by absorbing fine particulate matter along with the gaseous pollutants [20, 21]. The entire area of the rear vertical surface (South facing wall) of the Visvesvaraya block is approximately 1020m² (Fig 20). A green façade retrofit, draped with the established plant species, Vernonia Elaeagnifolia and Passiflora Caerulea, is permanently aligned on to the rear walls of the Visvesvaraya Block (Fig 20).

Figure 20. The rear side green façade wall of the VB – wall Area 1020m²

Figure 21. The view of a living wall (long view and close view) at the entrance of the Visvesvaraya Block, SAINTGITS Campus, Kottayam, Kerala, India.

These living retrofits can alleviate the pollutant level. For certain buildings, the walls itself will act as living walls – the greenery directly sticks on to the building fabric (Fig 21). In such cases, the durability of the external fabric is of great concern. Earlier experimental studies at Vellore Institute of Technology (VIT), Vellore, Tamilnadu, India have proved the capability of the vertical greeneries to cleanse the atmosphere [5]. The hanging foliage on both sides of the underpass always kept the atmospheric pollutant concentration at VIT, well inside the permissible limits.

Figure 22. Pruned green creepers act as natural atmospheric cleansers and alleviates the urban heat.

The concentration of Total Suspended Particulate Matter (TSPM), Respirable Particulate Matter (RSPM), the oxides of both Sulphur (SOx) and Nitrogen (NOx) were respectively 161µg/m³, 48µg/m³, 3µg/m³ and 6µg/m³ [1]. However, the concentration of NOx was nearly double the concentration of
SOx. The well pruned green creepers at the sides of highways can naturally cleanse the atmosphere to a greater extent [22]. It also renders excellent visual treat (Fig. 22).

The green creepers, *Vernonia Elaeagnifolia* (*VE*) and *Passiflora Caerulea* (*PC*) are used, exclusively at two different instances [1]. Whilst the former freely falls as curtain vines from the top of high rise structures, the latter needs perfect support system (trellis) and is best suited for lower altitudes [5]. Even though the average leaf area of *VE* (760mm$^2$) is much lesser than *PC* (1600mm$^2$), the growth rate of the former is faster. Hence, it is concluded that the green creeper, *Passiflora Caerulea* is an excellent sink to alleviate the vehicular pollution that usually happens at lower altitude from the road surface. An altitude dependent pollutant deposition pattern is visible in *Vernonia Elaeagnifolia*, which is best suited for high rise structures [1].

The wind speed and the wind direction contributes to the pollutant dispersion pattern. The atmospheric pressure experienced at the surface of the vertical green foliage depends on the wind direction and the wind speed. As discussed in section 3.3, the predominant wind directions at the geographical locale of the Visvesvaraya Block, recorded for the month of June 2019 are from South (S) and South South West (SSW). For more than 30% of the time, the wind from the latter direction blew at a speed ranging from 3.6m/s to 5.7m/s.

To analyze the effect of wind speed and wind direction on the green façade (retrofitted at the rear wall of the VB), a model was created and analyzed in ANSYS Fluent [23]. The control volume was spacious enough to accommodate the entire green retrofit. To simultaneously analyze the results of both the South and the South South West (SSW) blowing wind, a replica of an inclined green facade wall too was modelled alongside – the South and the SSW directions are 22.5$^0$ apart (Fig. 23).

![Figure 23](image-url)  
**Figure 23.** The South and the South South West walls to emulate the wind directions – the pressure profile at both the wall surfaces are different.

As the wind blows at 6m/s, the pressure distribution on both the wall surface are noticeably different (Fig 24). On the south facing wall, more than 50% of the area experiences a pressure ranging from 234Pa to 259Pa. In fact, at the remaining part of the wall (closer to the top floors), the pressure dropped to a minimum of 7 Pa.

The particulate matter below 2.5 microns (PM$_{2.5}$) usually becomes airborne and the drop in pressure helps the fine particulate matter to settle at higher altitude. The green façade retrofit is capable to remove these pollutants. During the active hours of the day, abundant sunshine at the tropical climes keep the stomatal openings wider [24]. Hence, the pollutant removal rate (k) during day time is more that at night hours [1, 5, 24, 25]. Since k is dependent on the Leaf Area Index (LAI), for a LAI of 80%, the removal rate is $1.86 \times 10^{-7}$ / s [1, 24]. For the wind blowing from SSW direction, the pressure profile has an equal contribution, ranging from 385 Pa to 82 Pa. The tip of the topmost floor alone experiences a drastic pressure drop, takes the value to the negative range (Fig 24).
At a wind speed of 4 m/s, for both the South and the SSW directions, the maximum pressure recorded is 192 Pa. On the south facing wall, more than 80% of the area experiences a pressure ranging from 97 Pa to 129 Pa (Fig 25).

For a wind speed of 4 m/s, since the pressure drop is in the least range, the meteorological conditions are favorable for the maximum pollutant deposition to happen. Hence, it is inferred that the removal rate of the pollutants by the green façade drapes will be the maximum at 4 m/s than at 2 m/s & 6 m/s (Fig 24, 25 & 26).
4. Conclusions

Green façade retrofits are sustainable practices to alleviate the atmospheric pollutants. The removal rates of these green drapes will be at the peak when the stomatal openings are the maximum. Usually, the tropical region receives the maximum sunshine and therefore, the stomatal opening will be wider during the active day hours. Another favourable condition which enhances the removal rate is the drop in pressure at the green foliage boundary, an attribute of the medium wind speed—the maximum pressure drop near the façade surface is at 4m/s. Therefore, it is inferred that at medium breeze, a green façade retrofit to an existing built structures can efficiently remove the atmospheric pollutants. Hence, these sustainable initiatives have to be encouraged to utilize the natural capability of green façade retrofits to cleanse the atmosphere, thus helping to attain one of the seventeen Sustainable Development Goals (SDGs) of the United Nations (UN).

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