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The Impact of Green walls on Air Pollution and Thermal Comfort at Pedestrian Leven in Street Canyon

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Abstract: Urban areas grapple with challenges like poor air quality from traffic and increasing summer heat due to heat-absorbing surfaces such as concrete and asphalt. Green infrastructure offers solutions but faces limitations in urban settings. This study explores green walls as an alternative to improving air quality and outdoor comfort. Three scenarios were tested: base case (BC), green wall (GW), and green wall with trees (GW+T), using ENVI-met. The green wall's impact was prominent on the windward side against prevailing pollution. In the afternoon, it notably reduced NO_2 by up to 32% and PMs by 31% compared to BC. Additionally, green walls lowered mean radiant temperature by up to 5°C, especially in peak high temperatures. This study underscores the potential of green walls as an effective means of mitigating urban air pollution and enhancing summer outdoor comfort, especially when incorporated strategically.
Keywords: Green wall, air pollution, outdoor thermal comfort, street canyon, ENVI-met

1. Introduction

The World Health Organization (WHO, 2022) has reported a staggering 99% of the global population remains exposed to air pollution. The air quality within urban centres is often characterized as poor, marked by elevated levels of CO_2, NO_2, and PMs stemming from transportation-related emissions. Nevertheless, despite advancements in emissions reduction over the past decades, air pollution continues to represent the foremost environmental health concern in Europe (EEA, 2023).

Air pollution presents a significant peril to human health, extending its impact beyond respiratory and cardiovascular systems to encompass the intricate interplay with brain function and mental well-being (World Economic Forum, 2022). Furthermore, the pervasive presence of unyielding surfaces crafted from materials such as concrete, asphalt, glass, and steel, inherent to urban infrastructure like roads and buildings, holds the potential to reverberate deleteriously upon mental health and overall well-being.

In addition, urban centres experience even higher temperatures than the surrounding rural regions, a phenomenon referred to as the urban heat island (UHI) effect (Taha, 1997). This phenomenon can intensify summer temperatures to alarming levels. Urban environments, characterized by an abundance of artificial and low-albedo materials like asphalt and concrete, tend to absorb substantial solar radiation, causing surfaces to heat up significantly. Consequently, temperatures in urban centres surge, negatively impacting outdoor comfort and overall livability.

This study aims to assess the effectiveness of green walls in mitigating air pollutants and enhancing thermal comfort within street canyons. The analysis will specifically focus on how much PM and NO_2 reduction can be achieved through green wall integration. The improvement in outdoor thermal comfort will be evaluated through the influence of green walls on the mean radiant temperature.

1.1 Methodology

Three scenarios were simulated on ENVI-met to determine the effectiveness of green walls in reducing pollutants and improving outdoor thermal comfort: base case scenario (BC), green wall scenario (GW), and green wall with trees scenario (GW+T). London was selected as an idealised city to define the meteorological and pollution data. The street canyon measurement is 20.4m (H), 24m (W), and 100.5m (L) derived from the six streets analysed in the Marylebone area and pollution data was taken from DEFRA - London Marylebone monitoring site (DEFRA, no date).

2. Theoretical Background

Canyon geometry affects the ventilation rate and amount of solar radiation inside the street canyon which impacts air pollution and thermal comfort (Oke et al., 2017). Aspect ratio (AR), the height of the building, and the spacing between the two rows of buildings (H/W) stand as a crucial morphological indicators in street canyon, representing the openness of space relative to the sky (Oke et al., 2017). The AR can be categorised as regular (H/W=1), avenue canyon (H/W=0.5), and deep canyon (H/W=2)(Vardoulakis et al., 2003). Wind flowing in the perpendicular direction to the street canyon is a highly polluting condition as it creates a vortex inside the canyon recirculating the air pollutants back and accumulating on the leeward side (Ebadi Borna, 2022; Vardoulakis et al., 2003; Xie, Huang and Wang, 2005). The heating of walls in the street canyon due to solar gains induces thermal buoyancy, which can alter the formation and strength of vortices within the street canyon (Ebadi Borna, 2022; Xie et al., 2005). The AR, sky view factor and orientation are the influential design parameters that affect both air pollution and outdoor thermal comfort at the pedestrian level (Dissanayake et al., 2021).

Integrating green infrastructure (GI) into the urban fabric can substantially enhance the quality of life and efficiency of a city, facilitated by the multiple benefits it brings forth. Vegetations in GI such as trees, shrubs, and lawns have the potential to improve air quality and reduce air pollution (Jayasooriya et al., 2017). GI exhibits a greater efficiency at depositing pollutants compared to smoother, artificial surfaces (Ebadi Borna, 2022). Moreover, GI can reduce high temperatures as radiative heat exchanges are lower in vegetated surfaces due to the redistribution of radiation (Alexandri and Jones, 2008).

Green walls are one example of GI that can deliver multiple benefits, including air purification, noise attenuation, mitigation of Urban Heat Island (UHI) effects, increased biodiversity, energy reduction through lower surface temperature, enhanced aesthetics, and improvements in health and well-being. (Manso et al., 2021; Manso and Castro-Gomes, 2015; Perini et al., 2011, 2011; Susca et al., 2022).

Pugh *et al*. (2012) analysis has shown that in-canyon vegetation offers a substantial reduction in air pollution at street level by as much as 40% for NO_2 and 60% for PM using green walls in street canyon. Abhijith *et al*. (2017) reported that green walls will be an effective air pollution strategy because it does not disrupt the ventilation rate when compared to high-level vegetation such as trees. Viecco *et al.* (2021) found that a 25% coverage ratio of green walls is optimal for PM capture.

The capture of PM by vegetation primarily operates through two mechanisms: deposition and dispersion. Deposition can manifest in two forms—dry deposition and wet deposition (Ysebaert et al., 2021). Leaf morphologies such as hairiness, roughness, and leaf size have been reported to influence PM capture. (Hellebaut et al., 2022). Gaseous pollutants like NO_2 can be absorbed by the leaves through their stomata. (Okano et al., 1988).

There is a strong correlation of evapotranspiration rate (ET) and surface albedo (SA) in reducing mean radiant temperature (T_{mrt}) (Tan *et al.*, 2015). Cameron, Taylor, and Emmett (2014) found that the surface temperature behind the green wall was up to 7°C cooler than the bare wall, and in front of them, air temperature was 3°C lower. This cooling effect was most significant in plants with higher ET and wall leaf area index (WLAI), underscoring the importance of choosing suitable plant species for temperature reduction through ET and shading.

3. Analytical Work

The perpendicular wind exhibited pollution accumulation at the leeward side of the street canyon across all scenarios and conditions (Figure 2. and Figure 3.). During summer mornings, pollution levels were notably elevated on the leeward side. The effectiveness of green walls in reducing pollutants is evident only on the windward side across all conditions, particularly in the afternoon. During summer, compared to BC, the GW scenario is 32% and 30% more effective in reducing NO2 and PMs, respectively. This trend continues in winter, with GW remaining more effective by 30% in reducing NO2 and 31% in reducing PMs (Figure 1.). In the morning, during summer, the GW scenario is 8% to 9% more effective in reducing pollutants, while in winter, it is 11% more effective compared to BC. The addition of trees in the GW+T scenario did not result in a significantly higher reduction; it was only 1% more effective than the GW scenario across all conditions.

In oblique wind flow, pollution accumulates noticeably on the leeward side, closer to the downwind section of the street canyon (Figure 2. - d.-f. and Figure 3. - d.-f.). Unlike previous studies, the flow structure here does not exhibit helical vortex formation. The resulting wind flow behaves similarly to the parallel wind direction, but some portions are redirected by the windward building. This movement pushes pollutants from the street's centre to the leeward side towards downstream. The windward side, on the other hand, remains largely free of pollutants, with a dispersion rate reaching 98% across all scenarios and conditions.

In the parallel wind flow, the pollutants were dispersed from the centre of the street towards the downwind part of the canyon leaving no accumulation on either side of the street (Figure 2. - g.-i. and Figure 3. - g.-i.). The effect of green wall was inconclusive against this type of wind direction as all the scenarios exhibited no accumulation on the pavement area.

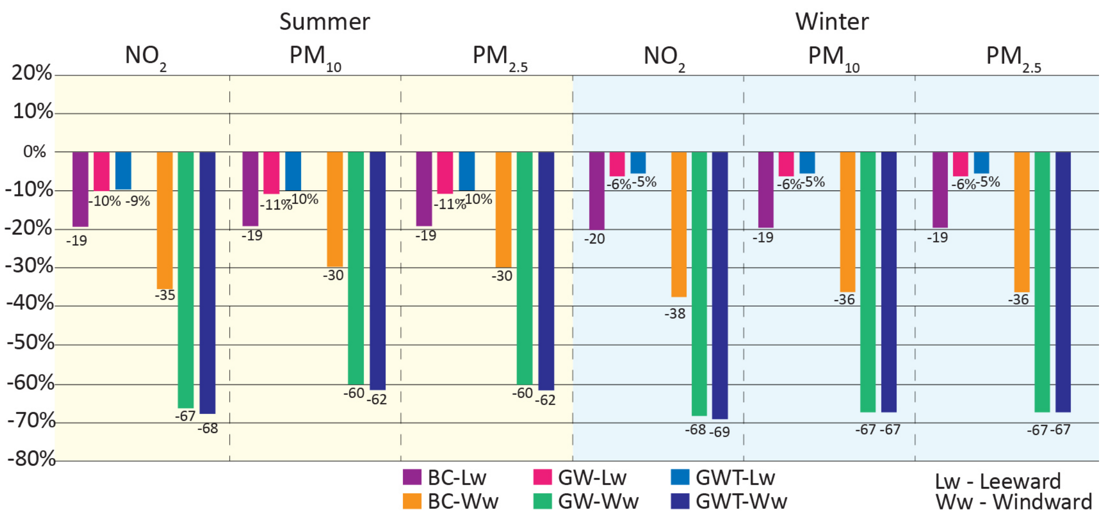

Figure 1. Pollution dispersion rate at 3:00 pm - summer and winter. The percentage between the pollution source in the centre (CR) and leeward (LR) or windward (WR). Negative value denotes lower concentration.

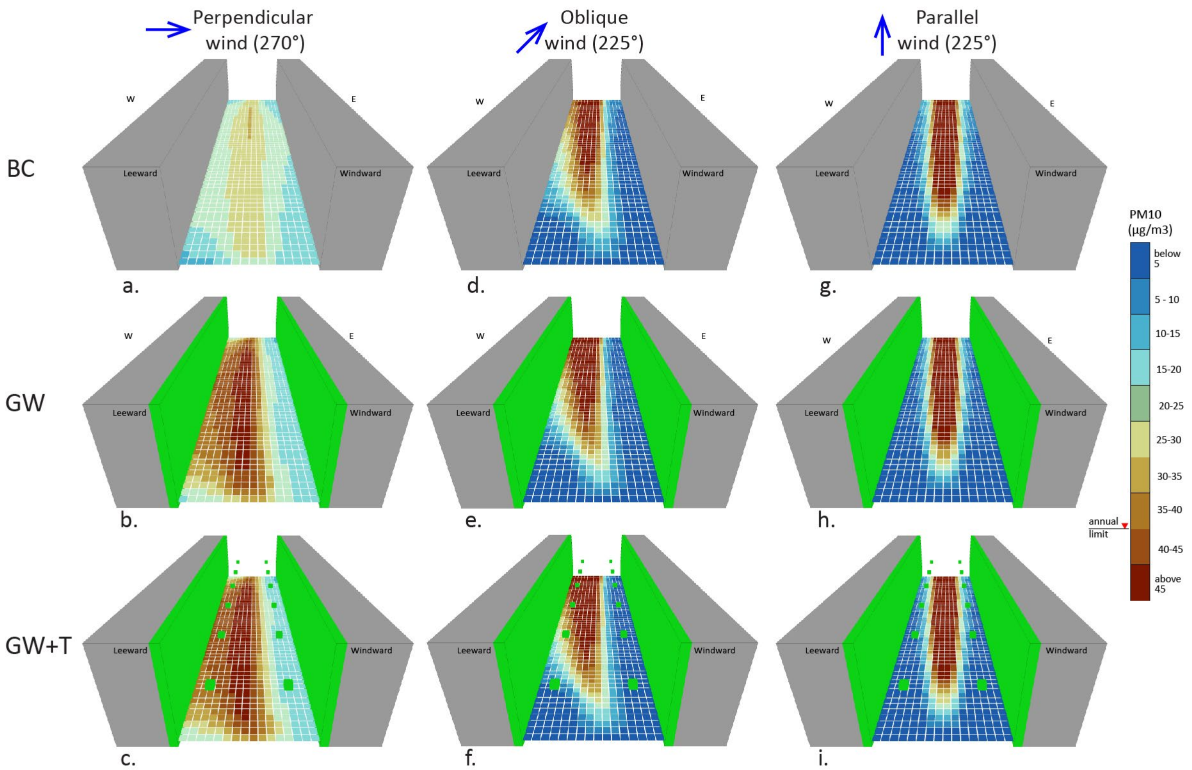

Figure 2. PM_{10} concentration in summer at 3:00 pm

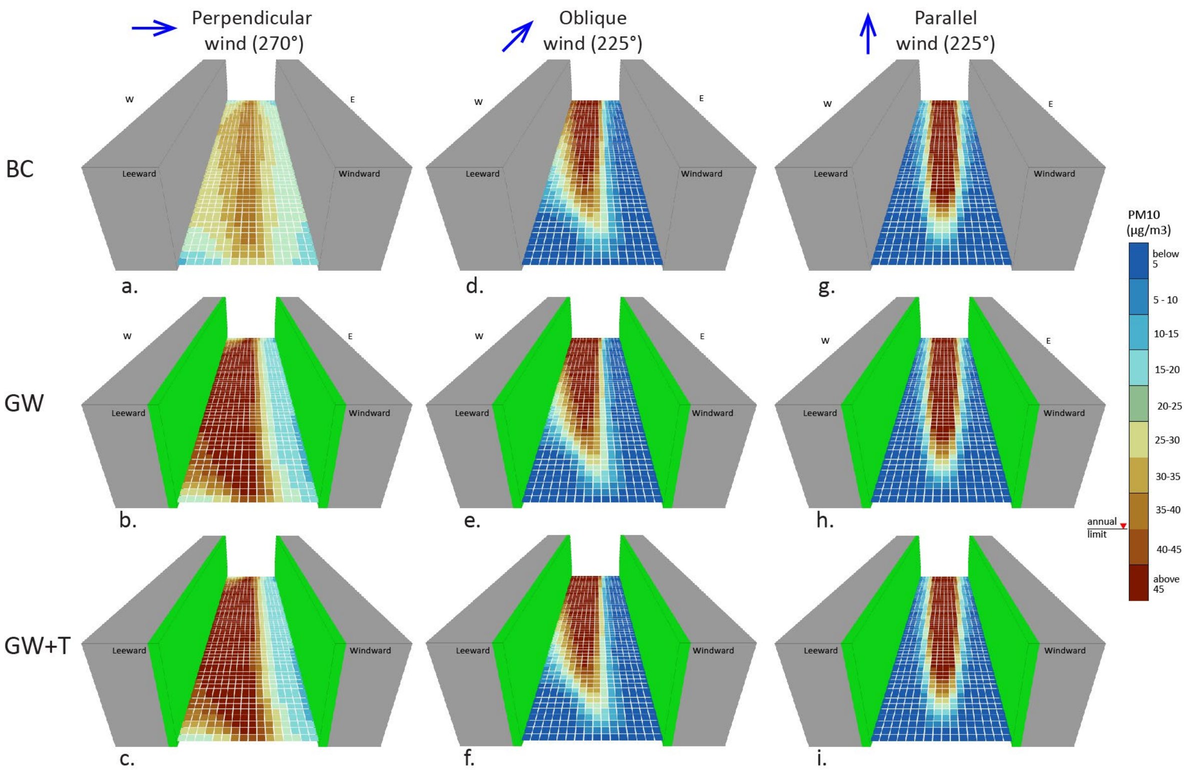

Figure 3. PM_{10} concentration in winter at 3:00 pm

The mean radiant temperature (T_{mrt}) reduction was most noticeable at peak hours, at 3:00 pm when the temperature reached 28°C. The green wall effectively lowered T_{mrt} by 5°C in both the GW and GW+T scenarios (Figure 4. - e. and f.). Conversely, at 12:00 pm, when the temperature was 25°C, T_{mrt} decreased by up to 4°C (Figure 4. - b. and c.). In the GW+T scenario, trees significantly reduced T_{mrt} in shaded areas by 18°C at 12:00 pm (Figure 4. - c.) and 24°C at 3:00 pm (Figure 4. -f.). Long wave radiation emittance is lower by 180 W/m^2 in the GW and GW+T scenarios compared to BC. This highlights that temperature reduction through shading is more effective at cooling elevated temperatures.

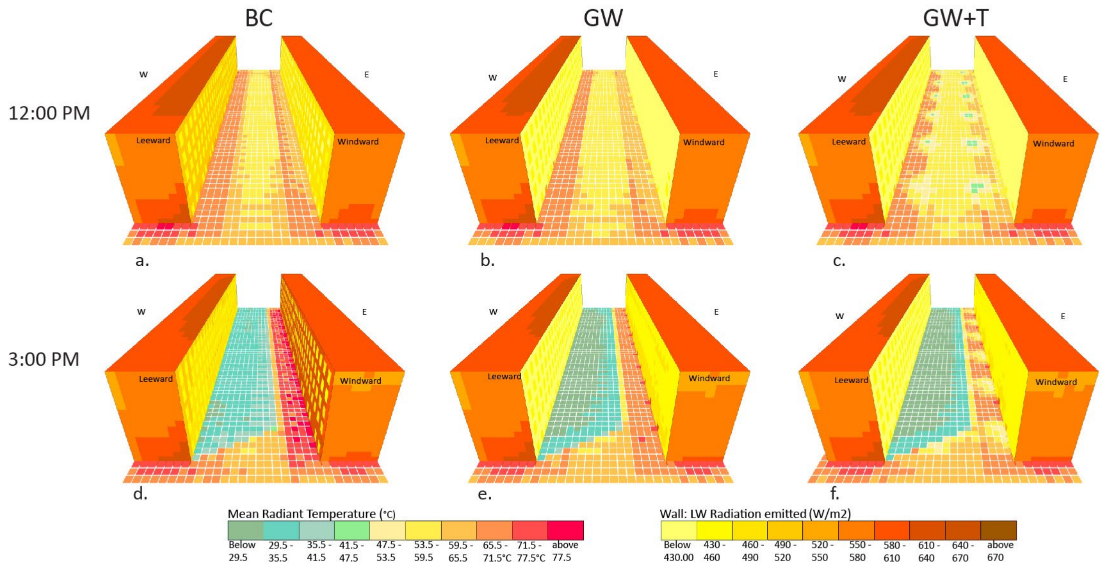

Figure 4. PM_{10} concentration in winter at 3:00 pm

4. Conclusions

The perpendicular wind flow scenario resulted in the highest levels of pollution. Across all scenarios and conditions, the leeward side pavement consistently exhibited the accumulation of pollutants. However, the impact of the green wall was evident only on the windward side pavement, where a more substantial reduction in pollution concentration was noted during the afternoon. Specifically, the green wall demonstrated greater efficacy in reducing NO_2 levels by **32% more** and PM levels by **31% more** compared to BC. In contrast to the reductions observed in the morning, the green wall's effectiveness was slightly reduced to 9% for NO2 and 8% for PMs.

The green wall demonstrated up to **5°C reduction** on the mean radiant temperature (T_{mrt}). This was observed during peak hour at 3:00 pm with ambient temperature reaching 28°C. The presence of trees significantly reduced the mean radiant temperature by **24°C** within the shaded regions. Emitted long wave radiation is lower by **180 W/m^2** in GW and GW+T compared to BC. This clearly indicates that temperature reduction through shading proves to be highly effective, particularly in mitigating high temperatures. Additionally, the impact of green wall is more pronounced when temperature is at peak.

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