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# Incorporation of Green Infrastructure on Road Tunnel Ventilation Stacks: Potential Ambient Air Quality Improvement

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## ABSTRACT

Vehicular tunnels are an important part of transportation infrastructure, though there are concerns about air quality due to the concentrated release of polluted air at roadway portals and tunnel ventilation stacks. Urban green infrastructure offers opportunities as a nature-based solution to mitigate urban particulate matter pollution. Green walls have advantages over other types of urban green infrastructure, since they can be potentially applied to large vertical surfaces available within cities and since they can be retrofitted onto already built structures. However, uptake of green wall technology has been limited on infrastructure projects, let alone the integration of green walls and roadway portals and tunnel ventilation stacks, which represents the first of its type worldwide. Therefore, this study aims to describe the integration of green wall technologies and a tunnel ventilation facility, and models the potential ambient air quality improvement the green wall plants have through $PM_{2.5}$ dry deposition. It was found that the project would increase ambient $PM_{2.5}$ to a concentration of 13.6 ug/m$^3$, and that the green walls would have the capacity to remove significant amounts of $PM_{2.5}$, from not only the ambient air pollutant increase as a result of the ventilation outlets, but also the background and surrounding surface road contributions. Differences in the rate of pollutant removed per stack by the green walls were attributed mostly to the varying ratios of plants installed. The findings indicate the air quality benefits of green wall integration on major infrastructure projects, which will assist in the overall sustainability appraisal of large infrastructure projects which need to balance the needs of population growth with environmental and human health.

**Key words**: *Green walls; Local pollution exposure; Particulate matter; Road tunnels; Ventilation systems*

## INTRODUCTION

Road tunnels are an important part of transport infrastructure, and a commonly used means to improve the flow of inner-city traffic, designed to meet the growing transport needs of a growing population (Van Brusselen et al., 2016). Road tunnels can help reduce air pollution by moving traffic off local roads, reducing emissions for the areas in which they bypass (Orru et al., 2015). Nevertheless, a road tunnel is a long, enclosed space, creating concerns due to the concentrated release of polluted air in the vicinity of roadway portals and tunnel ventilation stacks (Onay et al., 2019). Road traffic related air pollutants (TRAPs) have a substantial impact on health, with personal exposure associated with significant respiratory and cardiovascular effects (Shahriyari et al., 2022). The main TRAPs of concern include particulate matter (PM), nitrogen dioxide (NO2), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) (Demir et al., 2019; Song, et al., 2018). The most often used TRAP exposure indicator is PM with an aerodynamic diameter of 2.5 micrometres or less ($PM_{2.5}$), which is primarily generated by internal combustion engines, but also by the wear of tyres, brakes, and asphalt (Marinello et al., 2020). $PM_{2.5}$ is able to penetrate deeper into the lung's gaseous exchange region whereby it can enter the circulatory system, and cause health effects in other organs (Xing et al., 2016).

Tunnel ventilation stacks capture emissions from subterranean vehicles and release them into the surrounding atmosphere. Ventilation is required within tunnels to regulate emissions through the length of the tunnel, and is achieved by employing fan systems to propel the gases toward the tunnel portals and into ventilation stacks (Shepherd and Monson 2021). These ventilation stacks are designed to propel tunnel emissions into the atmosphere at a height greater than 20 meters above ground level where gases are diluted and mixed with the surrounding air theoretically resulting in little change to the quality of air for the surrounding community. While the presence of these tunnel ventilation stacks are critical to the operation of the road tunnel and for the safety of its users, what exists on the surface may be considered a visual 'eye-sore' to the community, and generate dialogue as to the safety of its function in relation to surrounding air quality. Tunnel ventilation stacks have a sustained negative connotation in the public eye due to their function of releasing traffic related air pollution and they are often opposed by the local community due to the fear that their health could be compromised (McManus and Haughton 2021).

Green wall technology has a significant opportunity to alleviate the negative public perception associated with ventilation stacks, by minimising the visual 'eye-sore' that the tall stack structures present to the community, replacing it with a biophilic experience (Hashad et al., 2021). The two conflicting notions of an egregious infrastructure entity and biophilia are resolved by the fact that these ventilation stacks are an essential aspect of long road tunnel infrastructure projects and that their existence and impact can be reduced via green wall technology (Iligan and Irga 2021). Further, green wall technology has the ability to functionally improve ambient air quality which has potential benefits when integrated with a tunnel ventilation facility. It is known that the plants that are grown in green walls have significant potential in urban regions as a sink for PM (Cui et al., 2022; Rowe et al., 2022). PM is removed from the ambient air by adhesion to leaf surfaces, with additional sequestration resulting from penetration of the wax layer of leaves if the PM contains organic pollutants of a lipophilic nature (Dzierżanowski et al., 2011).

This study addresses the more relevant process of dry deposition, which is the result of the removal of particles from the atmosphere onto the leaf through a transfer of particles by gravitational forces (Ysebaert et al., 2021). Vegetation characteristics such as leaf orientation, shape, size and surface morphology have been identified as significant factors associated with increased PM deposition (Paull et al., 2020). Macrostructural leaf traits that have been shown to increase PM accumulation include whorled leaf arrangements and larger leaf area (Irga et al., 2022); whilst advantageous microstructural traits include pubescence, low stomatal densities, rough surfaces and thick waxy epicuticles (Ysebaert et al., 2021).

Sydney, Australia has five extended motorway tunnels with advanced ventilation systems featuring ventilation stacks. These tunnels and their ventilation stacks include the M4 Extension, M5 East, and the Cross-City Tunnel (Figure 1). Recently, the NSW Government in Australia has initiated the M4-M5 link WestConnex Rozelle Interchange project which begun construction in 2019 and is projected to finish in December 2023. The project is part of the Sustainable Sydney 2030 Strategy and the Greater Sydney Region Plan to support Sydney's long-term economic growth and relieve road congestion. The project involves a series of tunnels to connect the 6.5 km M4 East tunnel, with the 7.5 km M4-M5 Link tunnel and the future 6.5 km Western Harbour Twin Tunnels that will be constructed under Sydney Harbour.

The $3.9 billion (AUD) project has been publicly controversial with criticism from local residents, citing air and noise emissions, and property value declines from tunnel construction (Hossain and Fuller 2021). A series of tunnel ventilation stacks are required on the project which will be covered in green wall technology (Figure 2). Uptake of green wall technology has been limited on infrastructure projects (Iligan and Irga 2021), let alone the integration of green walls and tunnel ventilation stacks which this project is the first to describe, worldwide.

Therefore, this opportunity represents a world first to describe a tunnel ventilation facility and the integration of green wall integration systems within Australia. This study will be the first of its kind to establish the impact green wall systems have on ambient air pollutants as influenced by ventilation stacks. To do this, atmospheric dispersion modelling was employed to quantify the potential increase in ambient particulates in the surrounding area as a result of the ventilation stacks' operation. Subsequently, the plants on the stacks were quantified and then assessed for the potential PM2.5 removal rate of the green walls through dry deposition.

**Figure 1**. Ventilation stacks for existing road tunnels across Sydney Australia. A.) Cross City Tunnel, B.) M4 Extension, C.) M5 East.

**Figure 2**. Tunnel ventilation stacks for the M4-M5 Link tunnel under construction and the final artist impression covered in green wall technology.

## METHODOLOGY

### Site Description

The M4-M5 Link Tunnels are approximately 7.5 km long and accommodate up to four lanes of traffic in each direction. Predicted traffic volumes are expected to be around 105,000 per average weekday in 2033. Within the tunnels, jet fans are used to supplement the vehicle piston effect, which is designed to ventilate 3,480 $m^3$ across the three stacks. The tunnel uses a longitudinal ventilation arrangement, with ventilation plants at all traffic exit portals to ensure net inflow of air, to prevent portal emissions. Each stack corresponds to a unidirectional tunnel. The scale of the chimneys is approximately 40 m from road height, the equivalent of about 12 storeys. The ventilation system's operating parameters vary depending on traffic volume and emissions. The volume of air to be extracted from the tunnels, and hence the number and output of the fans in use, would therefore vary by time of day. This would result, in turn, in hourly-varying outlet exit velocities, and emission rates. The pollutant concentration limit for ventilation outlets is set at 1.1 $mg/m^3$ for $PM_{2.5}$, though the existing road tunnels in Sydney have actual average concentration in the range of 0.05–0.30 $mg/m^3$.

### Green Wall Description

Each stack has green wall modules integrated into its design. Each module (0.5 x 0.5 x 0.15 m) was made from recyclable low-density polyethylene, with a front face of 0.25 $m^2$ that contains 16 holes from which plants can grow. The internal space within the modules is filled with a coconut husk-based plant growth substrate. A sheet of high-density polyethylene shade cloth lines the internal surfaces of the modules to contain the plant roots and growth substrate within the module. At the time of writing, the green walls are relatively new, with all plants at the same stage of the life cycle (Figure 3). This meant they were similar size and shape, having been maintained for four months within the nursery before implementation. The species of plants in use were selected for their suitability for full sunlight exposure on the open motorway, their low maintenance and water requirements, and their small (<1 m) full grown size. Further, these plants have been shown to be effective in exposed green walls because of fibrous root systems that effectively contain the substrate, a strong connection between the plant and the root system, the ability to contain themselves within the modular green wall structure and not be deciduous, demonstrate excessive growth habits, and phototropism that will detract from their aesthetic appearance.

### Data Collection and Analysis

Data was collected to identify the predicted rate of PM removal the green walls could exhibit due to their proximity to the tunnel ventilation outlets. Firstly, the plant species present within the green walls were recorded, whereby their individual microstructure and macrostructure properties were identified. To calculate the rate of pollutant removal, the mechanism of PM dry deposition was determined. Modelled values were taken from the Rozelle Interchange environmental impact statement in order to calculate the approximate $PM_{2.5}$ deposition flux.

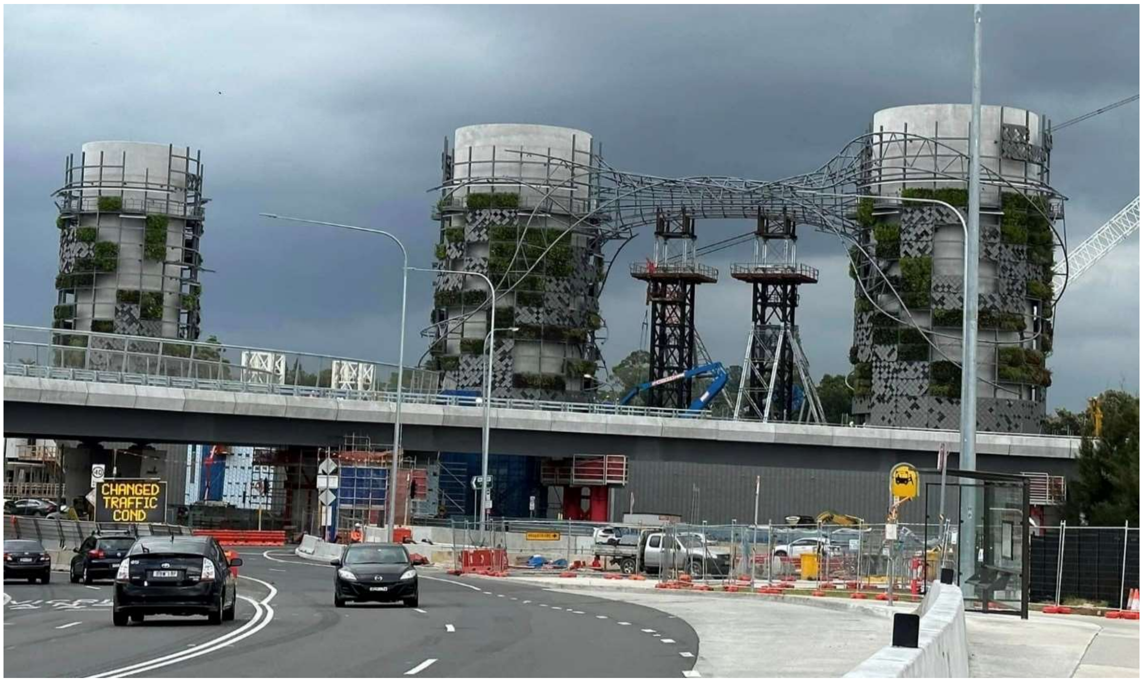

**Figure 3**. Tunnel ventilation stacks with completed installation of all the green wall modules. Ventilation stack 1 is furthest to the right, followed by Ventilation Stack 2 in the middle, and Ventilation Stack 3 on the left.

The environmental impact assessment for the project implemented the GRAMM/GRAL system for the dispersion modelling. This system uses the Graz Mesoscale Model (GRAMM) for prognostic wind field modelling and the subsequent dispersion model (GRAL), where GRAMM is the meteorological driver for the GRAL system. Within the modelling system receptors were used, these were split into community receptors which were particularly sensitive locations such as schools and hospitals, as-well as Recreational, Workplace and Residential (RWR) receptors located along the project corridors. There were 40 community receptors and 86,375 RWR receptors in total used within the model, which was based on expected traffic forecasts for the year 2033. This represented the theoretical maximum changes in air quality for all potential traffic operations in the tunnel, including unconstrained and worst-case traffic conditions from an emissions perspective, as well as vehicle breakdown situations.

The relative percentages of plant species used are shown within the Rozelle green walls across all stacks (Figure 4). The deposition flux for particular plant species was calculated through the following equation:

$$Fx = V_{dx}\ C_x$$

The deposition flux was calculated as the product of the deposition velocity ($Vdx$) of PM to the surface area of the plant species on the green wall and the concentration of atmospheric PM ($Cx$) in the ambient air which surrounds the tunnel ventilation outlet. The deposition flux of the individual plant species can be used a determinant of the PM removal rate of the total green walls on the three tunnel ventilation stacks.

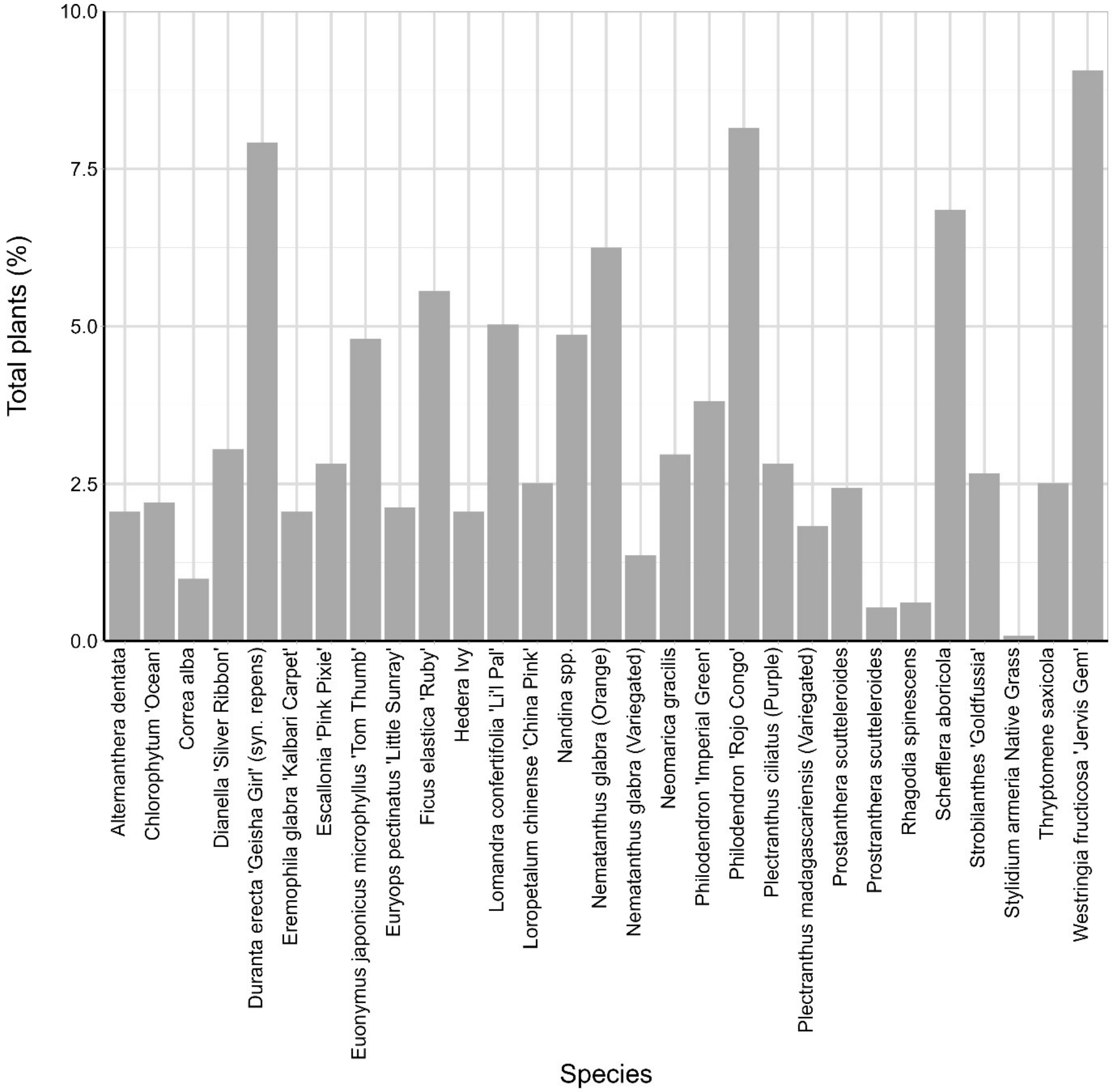

**Figure 4**. Percentage of plant species used within the Rozelle green walls across all stacks.

To generate these results, the deposition velocity of the plant species present on the green wall was required. There were limited studies available for the majority of the plants present on the green wall, however a comparison of plant morphology was performed to find a direct link to already researched deposition velocity values shown (Table 1). The plants were compared based on their physical form, leaf size and external structure to ensure the validity of the values.

Next, total plant area was quantified to calculate the removal rate of the entire green wall. The green wall module design was taken into consideration, to estimate the total plant coverage of the ventilation towers. After the deposition velocities per individual plant species was determined, this data was used in combination with the total plant area to calculate the removal rate of the entire green wall and each of the stacks. This was achieved by finding the total green wall area and then finding the area per plant species by dividing individual green wall module areas by their plant composition percentages. Then the data was averaged across the whole green wall to get total plant area per species. As this calculation only finds the area within a 2D plane, the deposition potential is underestimated, however this is further elaborated upon in the discussion section.

All graphics were generated using R version 4.0.4 (RDevelopment CORE TEAM 2009) and the following packages: ggplot2 (Wickham 2016), tidyr (Wickham and Henry 2020), xlsx (Dragulescu and Arendt 2012). Due to limited existing research on green walls on tunnel ventilation stacks, certain assumptions were made to aid analysis which will be elaborated upon in the below sections.

**Table 1**. Depositional velocities of PM relevant to the plants on the studied green wall.

| Species | Equivalent plant with similar phenology | Vd (cm/s) | Vd (m/h) | Source |
|---|---|---:|---:|---|
| *Alternanthera dentata* | *Populus deltoides* | 0.12 | 4.32 | (Beckett et al., 2000) |
| *Chlorophytum* | *Podocarpus macrophyllus* | 0.237 | 8.532 | (Yin, et al., 2019) |
| *Correa alba* | *Tsuga canadensis* | 0.0193 | 0.6948 | (Pullman 2008) |
| *Dianella* | *Podocarpus macrophyllus* | 0.237 | 8.532 | (Yin, et al., 2019) |
| *Duranta erecta* | *Prunus cerasifera* | 0.374 | 13.464 | (Yin, et al., 2019) |
| *Eremophila glabra* | *Tsuga canadensis* | 0.0193 | 0.6948 | (Pullman, 2008) |
| *Escallonia* 'Pink Pixie' | *Elaeocarpus decipiens* | 0.334 | 12.024 | (Yin, et al., 2019) |
| *Euonymus japonicus* | *Elaeocarpus decipiens* | 0.334 | 12.024 | (Yin, et al., 2019) |
| *Euryops pectinatus* | *Tsuga canadensis* | 0.0193 | 0.6948 | (Pullman, 2008) |
| *Ficus elastica* 'Ruby' | *Fiscus nitida* | 0.004 | 0.144 | (Freer-Smith et al., 2005) |
| *Hedera Ivy* | *Acer campestre* | 0.08 | 2.88 | (Beckett et al., 2000) |
| *Lomandra confertifolia* | *Pinus nigra* | 1.15 | 41.4 | (Pullman 2008) |
| *Loropetalum chinense* | *Cedrus deodara* | 0.319 | 11.484 | (Pullman 2008) |
| *Nandina* spp. | *Populus deltoides* | 0.12 | 4.32 | |
| *Nematanthus glabra* | *Elaeocarpus decipiens* | 0.334 | 12.024 | (Yin et al., 2019) |
| *Neomarica gracilis* | *Podocarpus macrophyllus* | 0.237 | 8.532 | (Yin et al., 2019) |
| *Philodendron* | *Magnolia grandiflora* | 0.305 | 10.98 | (Yin et al., 2019) |
| *Plectranthus ciliatus* | *Alnus glutinosa* | 0.125 | 4.5 | (Freer-Smith et al., 2005) |
| *Plectranthus madagascariensis* | *Populus deltoides* | 0.12 | 4.32 | (Beckett et al., 2000) |
| *Prostanthera scutteleroides* | *Tsuga canadensis* | 0.0193 | 0.6948 | (Pullman 2008) |
| *Rhagodia spinescens* | *Tsuga canadensis* | 0.0193 | 0.6948 | (Pullman 2008) |
| *Schefflera aboricola* | *Ligustrum lucidum* | 0.317 | 11.412 | (Yin et al., 2019) |
| *Strobilanthes* 'Goldfussia' | *Salix babylonica* | 0.277 | 9.972 | (Yin et al., 2019) |
| *Stylidium armeria* | *Pinus parviflora* | 2.853 | 102.708 | (Yin et al., 2019) |
| *Thryptomene saxicola* | *Tsuga canadensis* | 0.0193 | 0.6948 | (Pullman 2008) |
| *Westringia fructicosa* | *Tsuga canadensis* | 0.0193 | 0.6948 | (Pullman 2008) |

## RESULTS AND DISCUSSION

The concentration of $PM_{2.5}$ simulated for the year 2033 worst case scenario is shown (Table 2), the maximum total concentration of $PM_{2.5}$ was used for deposition calculations. The maximum concentration annual mean averaged across all RWR receptors was 13.61 $\mu g/m^3$. This total concentration considers the tunnel ventilation outlets while also establishing that the air quality will be affected by other sources in the background (58.7%) and surrounding surface roads at the ground level (40.8%).

$PM_{2.5}$ removal rate (µg/h) for each of the different plant species across all three ventilation outlet stacks is displayed (Figure 6). *Lomandra confertifolia* is the most prevalent plant, followed by *Duranta erecta*, and thus they have the highest pollutant removal rates, relative to the other plant species present.

**Table 2** The worst-case scenario concentration of $PM_{2.5}$ for the area as influenced by background concentrations, surface road concentrations and stack outlet concentrations, modelled for the year 2033.

| Predicted 2033 Residential, workplace and recreational receptors exposure annual mean (µg/m$^3$) | |
|---|---|
| Background concentration | 8.00 |
| Maximum surface road concentration | 5.56 |
| Maximum stack outlet concentration | 0.24 |
| Maximum total concentration | 13.61 |

When calculating the plant area for the removal rate, the green wall calculation outlined within the methodology section had several limitations. The total percent of plants across the entire project per ventilation stack is presented (Figure 7), showing large variation between the three stacks, a result of the aesthetic 'twisted steel' design elements that are featured on the stacks, which can be seen (Figure 3). By taking the surface area of the modules and dividing it by the area of the individual plants used, a realistic base calculation in the worst case can be made. This assumption of plant area was also made due to the fact that the green walls are relatively new, with plants of similar shape and size and therefore area. However, as they grow, this assumption will need to be revisited.

The results were then consolidated to each individual stack (Figure 8). The data presented is once again relative to the percentage of plants used on each of the stacks in relation to the total plants used (Figure 7). Ventilation stack 2 is predicted to be the most effective for the removal of $PM_{2.5}$. This can be attributed to its larger area with more plants and therefore more opportunity for dry deposition to occur. The total $PM_{2.5}$ removal rate for the whole set of green walls on the tunnel stacks combined is predicted to be a substantial 2,547.12 µg/h (Figure 8).

However, given that the ambient air pollution profile of $PM_{2.5}$ in addition to the modelled stack outlet contribution of is 13.61 µg/m$^3$, the total green wall size required to completely scrub all of this pollutant from the local ambient air is substantially larger. If the combined stack flow was 10 m/s then around 10 mg/m$^3$/s of PM would be generated at the maximum allowable limit for $PM_{2.5}$ emission, or around 36 000 000 µg/m$^3$/h. In the context of this project, mitigation of this emission level is not achievable, although the substantial planted sporting fields and blue-green infrastructure that will be added in the future (Figure 2), may provide sufficient additional plants to partially achieve this. It is important to note that the authors, nor the developing authorities for the project, propose that the green wall should act as a complete air pollutant scrubber for the stacks.

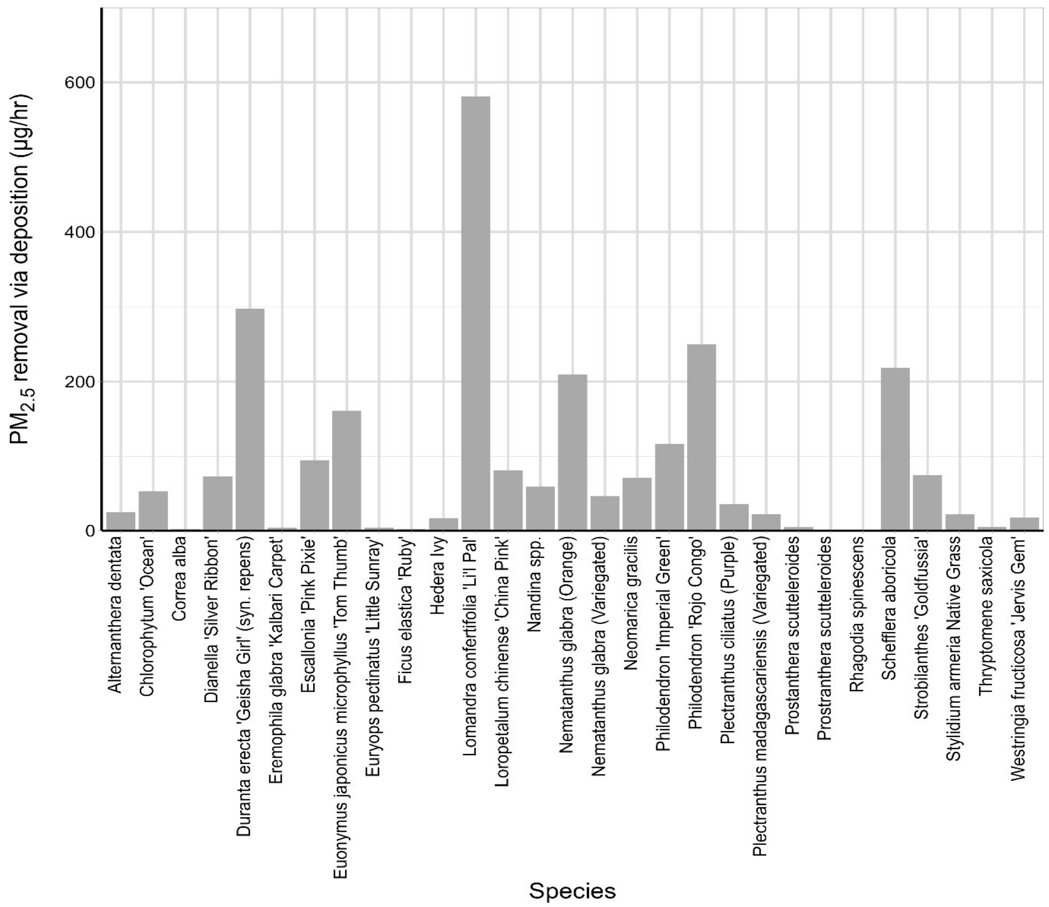

**Figure 6**. Pollutant removal rate per plant species (µg/h) across the 3 green walls.

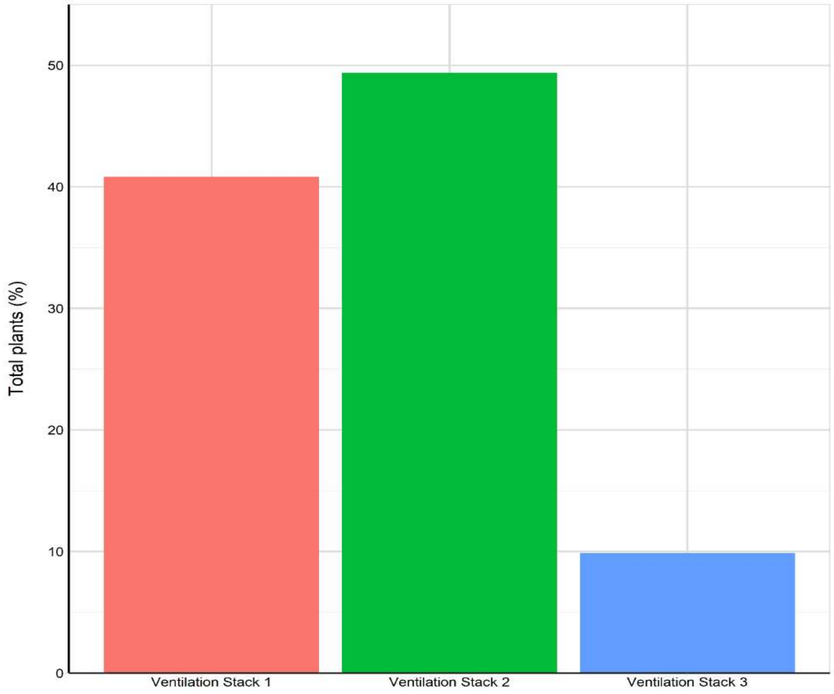

**Figure 7**. Percent of plants across the entire project used per ventilation stack.

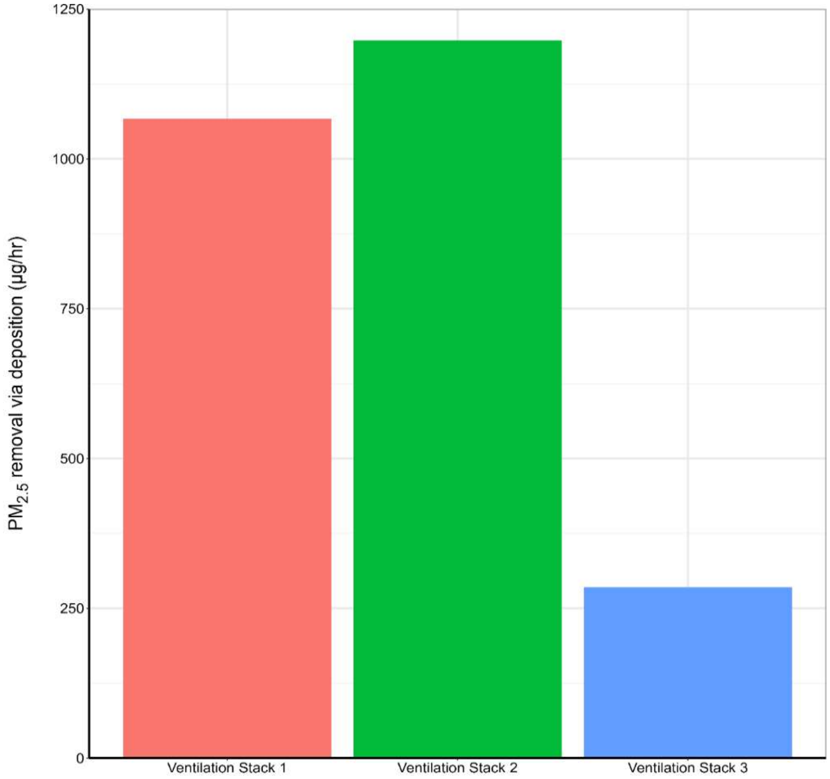

**Figure 8**. Pollutant removal rate by plants through deposition per ventilation stack.

The transport network in Sydney is expected to be put under increasing pressure over the next 20 years, with Sydney's population forecast to increase from 4.3 to 5.9 million, which equates to an average of 80,000 additional residents per year. Moreover, by 2036, the number of motor vehicle trips made around Sydney each day is forecast to increase by 31% from 16 to 21 million vehicle movements (Desa 2019). The rise in urban living will be a key driving force in governmental investments in large infrastructure projects, to enable the efficient and reliable transport of people around increasingly densely populated centres. For this reason, providing efficient and technologically-advanced infrastructure networks are a priority for governments to improve the social and economic value of urban cities, but the impacts on the surrounding environment are often neglected (Searle and Legacy 2020), including the current described project. Concerns about the motorway project resulted in a regional government parliamentary inquiry into the project's impacts (Robertson et al., 2021).

A substantial 556 submissions were made to the inquiry, with most (63%) individual submissions mentioning air pollution and health as the issues of concern. Further, most submissions (64%) were concerned with the cost-benefit analysis, including concerns that the health impacts were being underestimated and economic benefits overestimated. This notwithstanding, enabling sustainable development through lessening the environmental impact of major road networks has become an increasing trend within the construction and engineering industry (Curtis and Low 2016; Pettit et al., 2020; Pettit et al., 2021), though the authors acknowledge that these efforts are often neglected at various stages of the project, be they the planning, design, or operation stages, with the effects only observed years after the completion of projects.

### Limitations

The calculations in this work are from the perspective of removal of the existing ambient air pollution profile, with the addition of the forecasted ventilation output from the tunnel ventilation facility. This means that our model is accounting for the background $PM_{2.5}$ concentration, and emissions from the surface roads, and the tunnel ventilation outlet. The $PM_{2.5}$ removal rate calculated would be much smaller if only the tunnel ventilation outlet $PM_{2.5}$ concentration was taken into consideration, as the current calculations use a potentially smaller pollutant concentration within the deposition flux calculations reducing the flux and subsequent removal rate. However, it is unrealistic to isolate the tunnel ventilation outlet concentration and ignore both the background and surrounding surface roads which are contributing to the overall $PM_{2.5}$ concentration.

Further, assuming that concentration limits are applied to the ventilation outlets, the results of the current analysis serves to demonstrate the air quality performance of the project if it operates continuously at the limits. In reality, ventilation outlet concentrations would vary over a daily cycle due to changing traffic volumes, tunnel fan operation, and prevailing environmental conditions, resulting in lower $PM_{2.5}$ emissions for large parts of the daily cycle than those used in our analysis. Similarly, this study assumes that future vehicles will be mostly fossil fuel powered — a greater transition to an electric vehicle fleet would also alter, but not negate, ventilation outlet particulate concentrations.

As discussed in the methods section, the plant area used was an average 2D plane value, as used in previous green roof evaluations using 2D digital image analysis (Bousselot, et al., 2010). This assumption satisfies the conditions of the calculations at the time of writing due to plants being of the same size and shape. However, as time passes, the individual plant species will grow and die accordingly to their characteristics and climate (Schneider et al., 2014) and will therefore consequently have varying size and shape. In the future, the exact leaf area of the individual plant species will need to be determined for increased accuracy. This would mean finding the average full-size leaf area of each of the plant species, through measuring a range of leaves for that species.

## CONCLUSIONS AND FUTURE DIRECTIONS

This study has provided an insight into the potential societal and environmental benefits of the green walls implemented on the Rozelle Interchange tunnel ventilation facility. As the implementation of a green wall on a tunnel ventilation outlet is a world first, there is no existing literature for context and foresight. Therefore, it is imperative that the green walls continue to be monitored as construction continues and the plants grow and settle into the future. As stated above, the plant calculations were based on 2D digital image analysis, therefore, future work should consider the 3D plane, ensuring that the surface area of each leaf within the green wall module is considered. Similarly, it is recommended that in the future that additional studies must be conducted to revisit the removal efficiency of the green walls as the plants grow bigger, and therefore have an increased surface area and thus a larger deposition flux.

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