Conceptual Framework for Planning Urban Roadside Vegetation to Enhance Air Quality for Roadside Users

Soujanya Mogra
Department of Architecture and Urban Planning, College of Engineering, Qatar University, Doha, Qatar
sm1513220@student.qu.edu.qa

Mohd Faris Khamidi
Department of Architecture and Urban Planning, College of Engineering, Qatar University, Doha, Qatar
mohd.khamidi@qu.edu.qa

Fodil Fadli
Department of Architecture and Urban Planning College of Engineering, Qatar University, Doha, Qatar
f.fadli@qu.edu.qa

Abstract

Vegetation is known for enhancing air quality. However, vegetation on urban roads can either increase or decrease exposure to air pollutants. The health of pedestrians and cyclists is particularly of great concern since they are exposed directly to air pollutants, unlike drivers. Dispersion of air pollutants is necessary for exposure reduction on urban roads. The local factors, including street geometry, meteorological conditions, and physical characteristics of vegetation, influence the dispersion of pollutants. There is a lack of framework for planning urban road vegetation to disperse air pollutants. This study summarizes the literature on the influence of local factors; analyses the interrelation between the local factors on the dispersion of air pollutants by trees and hedgerows. It provides a conceptual framework to provide clarity in planning urban roadside vegetation to enhance the air quality for roadside users.

Keywords: Urban roadside vegetation; Dispersion of air pollutants; Well-being of the roadside users; Conceptual Framework

1 Introduction

Urban vegetation is widely known for enhancing air quality. Ambient pollutants are reduced by vegetation through absorption and deposition, as well as dilution through dispersion (Garland, 2001). Vehicular traffic on urban roads is one of the main contributors to air pollutants in cities (World Health Organization, 2022). Accumulated air pollutants over a prolonged period in urban streets are detrimental to the health of road users. The health of roadside users, i.e., pedestrians and cyclists, are particularly at risk from traffic-borne air pollution since they are exposed directly to the pollutants, unlike drivers, who are partially protected. The ability of the street vegetation to disperse air pollutants plays a significant role in reducing roadside users' exposure to traffic-borne air pollutants.

Studies on the dispersion of air pollutants in street canyons have examined the influence of wind conditions (Baik & Kim, 1999; Huang et al., 2019); street geometrical characteristics (Hunter et al., 1992; Oke, 1988); variations in surface temperature (Xie et al., 2005; Xie et al., 2007). Studies have looked into the effect of vegetation on pollution dispersion in street canyons (Amorim et al., 2013;

Buccolieri et al., 2009; Gromke et al., 2016; Li et al., 2016). There are reviews on the deposition and the dispersion of air pollutants by street vegetation (Abhijith et al., 2017; Janhäll, 2015). In addition, Hewitt et al., (2020) discussed where and how certain vegetation forms improve air quality in different urban environments. Trees and hedgerows are common street elements. However, there is no clarity on planning trees and hedgerows in street canyons to reduce roadside users' exposure to air pollutants. Hence, a conceptual framework for planting trees and hedgerows to disperse air pollutants is worth developing. This study provides a conceptual framework for planning trees and hedgerows to enhance the dispersion of traffic-borne pollutants in street canyons.

2 Local Parameters

2.1 Street Geometry

Local urban spatial form and building regulations determine the geometrical characteristics of urban roads. 'Aspect ratio' is used to express the geometry of street canyons. 'Aspect ratio' is defined as the ratio of the building height (H) and the width of the street (W). Aspect ratios fall into one of three categories: shallow, which has aspect ratios less than 0.5; regular, which has aspect ratios between 0.5 and 2; and deep, which has aspect ratios greater than 2 (Abhijith et al., 2017; Vardoulakis et al., 2003). Street canyons are subcategorized into short, medium, and long based on the street canyon length (L) and street canyon height (H). The short canyon has $L/H \approx 3$; the medium canyon has $L/H \approx 5$; and the long street canyon has $L/H \approx 7$ (Vardoulakis et al., 2003).

When the wind direction is perpendicular to the street canyon, as shown in Figure 1, the airflow regime, i.e., the number of vortex formations and strength of the vortex, varies according to the street aspect ratio (Oke, 1988) and street canyon length (Hunter et al., 1992). In an isothermal condition, three types of airflow regimes are observed by Oke (1988), as shown in Figure 2. When $H/W < 0.33$, the vortex formed at the windward and leeward walls, has no interactions, as shown in Figure 2 (a), which is known as 'isolated roughness flow.' When $0.33 > H/W <0.66$, the vortex near the windward and the leeward wall interfere, as shown in 2 (b), which is known as 'wake interference flow' When $H/W > 0.66$, a single complete vortex is formed as shown in 2 (c), which is known as 'skimming flow.' The transitions between airflow regimes occur at critical combinations of aspect ratio and length ratio (Hunter et al., 1992). Shallow and short-street canyons are better ventilated.

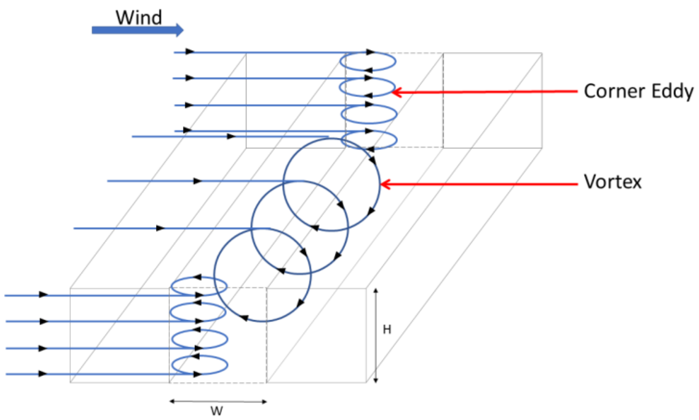

Fig. 1: Formation of vortex and eddies in a square street canyon (H/W=1)

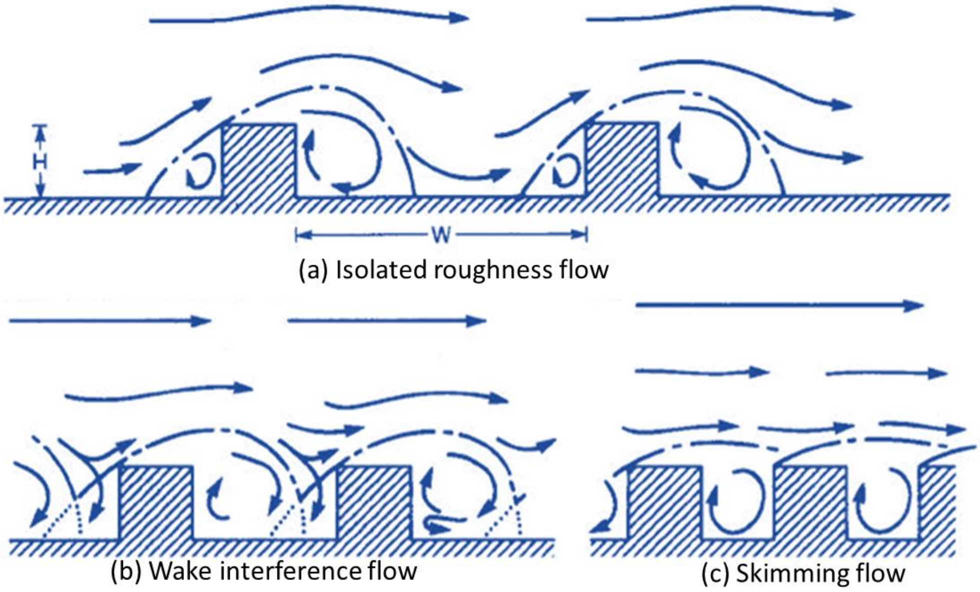

Fig. 2: Airflow regime in street canyons

Trees form a relatively complicated flow field, and the street aspect ratio does not influence the formation of vortices in the presence of trees (Wang et al., 2020). A study conducted by Buccolieri et al. (2009) showed that the effect of trees on the dispersion of pollutants decreases with an increase in aspect ratio, irrespective of the form and arrangement of trees. A study by Zhu et al. (2022) showed that a central greenbelt and a greenbelt on the leeward side of the street canyons are effective in pollutants' dispersion in street canyons having lower aspect ratios with aspect ratios less than 0.67.

2.2 Wind Direction

Typically, the wind directions perpendicular, parallel, and oblique to the street canyons are studied. When the wind is perpendicular to the street axis, the pollutants accumulate at the leeward bottom with a greater concentration at the canyon's centre. When the wind is oblique to the street axis, the pollutants build up at the leeward side of the downwind part of the canyon. When the wind is parallel to the street canyon, the pollutants accumulate in the downwind area (Vardoulakis et al., 2003; Yazid et al., 2014).

Studies show that trees perform better at dispersing pollutants when the wind is parallel to the street axis. For example, Amorim et al. (2013) in Portugal showed that when the wind direction was roughly 45°, CO concentration was increased by 12% in the street canyon with an aspect ratio of 0.33. When the wind is parallel, trees decreased CO concentration by 16% in the street canyon with an aspect ratio of 0.75. A study by Gromke & Ruck, (2012) showed that wall averaged pollutant concentration was higher in street canyon with avenues of trees compared to the tree-less street canyon. Wall averaged pollutant concentration in street canyon with avenues of trees was highest for oblique wind and lowest for parallel wind. Zhu et al. (2022) showed that a central greenbelt and a greenbelt on the leeward side of the street canyons are effective in reducing pollutants exposure of roadside users when the wind direction is almost perpendicular in street canyons with an aspect ratio less than 0.67.

A study by Gromke et al. (2016) showed that the presence of a central hedgerow in a street canyon of an aspect ratio of 0.5 reduced the area-averaged reduction of pollutant concentration by 46–61% at pedestrian head height level on the leeward side. Two sideways-arranged hedgerows reduced area-averaged pollutant reduction on the leeward side between 18 and 39% at pedestrian head height. In the case of parallel wind direction, two sideways arrangements of hedgerows reduced the area-average pollutant concentration up to 60% at the head height of the pedestrians.

2.3 Wind Speed

Lower wind speeds weaken street ventilation by reducing vertical air mixing between the in-canyon volume air and the air above in the atmosphere. Higher wind speed enhances vertical air mixing by strengthening the vertices and has a significant role in pollutants' dispersion Zhang et al., (2015).

Niroobakhsh et al. (2021) revealed that an increase in ambient wind speed does not affect the number of vertices; however, it increases turbulence intensity and strength of the vertices. Nazridoust and Ahmadi (2006) observed the vanishing of the secondary vortex at the bottom upwind corner when the wind speed increased to 20 m/s from 1 m/s in a regular street canyon. Further, Baik and Kim (1999) observed the merging of the two secondary vertexes into a primary vortex at the canyon bottom in a deep street canyon when the wind speed increased from 1m/s to 4m/s. Additionally, the study found a threshold for the wind speed above which the number of vortices did not change.

Ries and Eichhorn (2001) observed an increase in volume averaged pollutant concentration when the speed was reduced to 5m/s from 6 m/s in a street canyon with an aspect ratio of 0.5 in the presence of trees. A study by Zhu et al. (2022) on Qianfoshan Road in Jinan, China, showed that a central greenbelt and a greenbelt on the leeward side of the street canyons are effective in pollutant exposure reduction in moderate to higher wind speeds. The study found an increase in exposure to PM2.5 when the wind speed was 2.45m/s and perpendicular to the street axis. When the wind speed increased from 2.45 to 4.7 m/s, 4.7 to 6.7 m/s, and 6.7 to 9.35 m/s, the residence time of PM2.5 decreased by 78%, 51%, and 40%, respectively.

A study by Li et al. (2016) showed that the optimum height of a hedgerow is 1.1 meters for the dispersion of pollutants in street canyons of an aspect ratio between 0.3 and 1.67. The study revealed that the dispersion of pollutants by hedgerows is not sensitive to wind speed when the wind is perpendicular to the street canyons.

2.4 Surface Temperature

According to the solar zenith angle and the weather during the day, buildings and street surfaces heat up. Studies by Xie et al. (2005) on a regular street canyon showed that when the leeward façade is heated, the airflow pattern remains the same as in the isothermal case. However, the vortex acquires greater strength due to upward advection flux along the leeward wall produced by buoyancy flux. Consequently, the pollutant concentration decreases when the windward wall is heated. On the other hand, when the windward façade is heated, the upward buoyancy flux produced opposes the downward advection flux and forms two contra-rotating vertexes. As a result, pollutant concentrations increase on the windward side. When the ground surface is heated, the buoyancy flux produces two counter-rotating vortices: one near the upper leeward wall and the other near the lower portion of the windward wall. With an increase in temperature, the clockwise vortex on the windward side expands, and the contraclockwise vortex on the leeward wall shrinks. As a result, pollutants accumulate on the windward side. However, overall, the pollutant concentration decreases in the street canyon when the ground is heated.

Di Sabatino et al. (2015) revealed that trees in the street canyon reduce the temperature at the bottom of the façade in a Mediterranean climate during the day. However, trees trapped heat closer to the ground and released the heat at night time. As a result, night time air and façade temperatures were higher in street canyons with trees than in street canyons without trees. In addition, the tree crown hindered vertical air exchange and created thermal stratification, which caused reversal airflow. As a result, volume-averaged concentration in the bottom of the street canyon increased.

3 Intrerelation between the Meteorological Conditions, Street Geometry, and Dispersion of Pollutants by Street Vegetation

Dispersion of pollutants by street trees is lower at lower wind speeds (Ries & Eichhorn, 2001). Pollutant concentrations are higher when the wind directions are perpendicular and oblique to the street canyon axis (Zhang et al., 2015; Huang et al., 2019). The presence of trees in street canyons slows down the airflow velocity (Buccolieri et al., 2011; Wang et al., 2020). Trees perform better when the ambient wind direction is parallel to the street axis (Amorim et al., 2013; Gromke & Ruck, 2012). The dispersion of pollutants by street trees decreases with an increase in aspect ratios (Buccolieri et al., 2009). When the street canyon ratio is less than 0.67 with optimal tree spacing, the Central Greenbelt (trees and hedgerows) and leeward greenbelt have the potential to disperse pollutants even when wind direction is perpendicular to the street axis (Zhu et al., 2022). Variation in wind direction, i.e., perpendicular to parallel, has more influence than the variation in aspect ratio between 0.33 to 0.75 on the dispersion of pollutants (Amorim et al., 2013). Variations in wind speed considerably influence the dispersion of pollutants by street trees (Zhu et al., 2022). Dispersion of pollutants by street trees increased with an increase in wind speed; however, not at the same rate (Zhu et al., 2022). Diurnal temperature influences the dispersion of pollutants by street trees (Di Sabatino et al., 2015).

Central hedgerows reduce wall-averaged pollutants at pedestrian height for perpendicular wind directions in shallow street canyons (Gromke et al., 2016). A sideways arrangement of two hedgerows performs better in pollutants' dispersion when the wind is parallel to the street axis (Gromke et al., 2016). The effect of hedgerows on pollutant dispersion is less sensitive to changes in wind speed (Li et al., 2016).

There is no simple association between the meteorological conditions and the dispersion of pollutants by street vegetation. Therefore, planning urban road vegetation for the dispersion of pollutants necessitates local investigations. Field experiments can be resource intensive as well as time-consuming. Hence, Computational Fluid Dynamics (CFD) method is popular among researchers. Software such as Ansys Fluent (Buccolieri et al., 2009; Gromke et al., 2016), Open Foam (Jeanjean et al., 2016; Jeanjean et al., 2017), and ENVI-met (Vos et al., 2013; Wania et al., 2012) are used in the investigations.

4 Conceptual Framework for Planning Urban Road Vegetation for Dispersion of Air Pollutants

This study recommends the below parameters in the simulations:

1. Street geometrical characteristics: the typical length of an urban block, building height, and coverage according to the local regulation.
2. Street orientation: orientation of the local street patterns such as gridiron, radial, and circular according to the prevailing wind direction.
3. Meteorological conditions: the seasonal variations, hourly variations.
4. Vegetation: physical characteristics such as height, width, vertical coverage, and leaf area density (LAD).

5. Pollutants’ Emission Rate: calculated using the Annual Average Daily Traffic (AADT)

   Figure 3 shows the theoretical framework for planning trees and hedgerows for pollutants’ dispersion in urban streets.

Figure 3 shows the conceptual framework for planning trees and hedgerows for dispersion of pollutants by street vegetation.

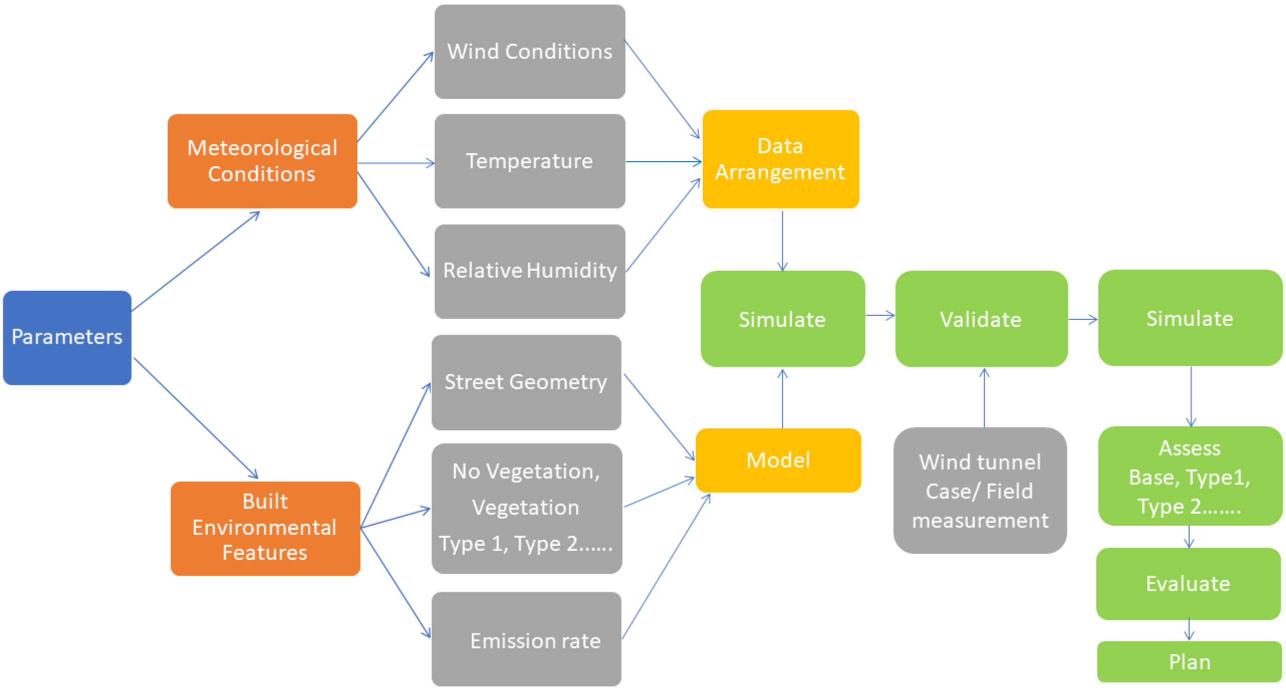

Fig. 3: Conceptual Framework for Planning Urban Road Vegetation for Pollutants’ Dispersion

5 Conclusion

Street geometry plays a crucial role in street ventilation. Vertical air exchange is higher in shallow street canyons than in regular and deep street canyons. Vegetation has less effect than street geometrical characteristics on the dispersion of pollutants. Hence, vegetation is suitable for shallow street canyons.

Trees perform better in the dispersion of pollutants when the prevailing wind is parallel to the street axis. Hedgerows perform better than trees in pollutant exposure reduction when the wind is perpendicular to the axis in shallow and regular street canyons. At low wind speeds, street trees are less effective at dispersing pollutants. Dispersion of pollutants by hedgerows is less sensitive to wind speed when the wind is perpendicular to the street axis. Therefore, the physical form of vegetation plays a crucial role in the dispersion of pollutants.

Changes to any parameter, including the meteorological parameters, vegetation form, and street geometry, can considerably influence pollutant dispersion by street vegetation. Therefore, all the local parameters should be considered together in the simulations to plan urban road vegetation to reduce roadside users’ exposure to pollutants.

References

Abhijith, et al. (2017). Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. *Atmospheric Environment*, *162*, 71-86. https://doi.org/https://doi.org/10.1016/j.atmosenv.2017.05.014

Amorim, et al. (2013). CFD modelling of the aerodynamic effect of trees on urban air pollution dispersion. *Science of the Total Environment*, *461-462*, 541-551. https://doi.org/https://doi.org/10.1016/j.scitotenv.2013.05.031

Baik, J. J. & Kim, J. J. (1999). A Numerical Study of Flow and Pollutant Dispersion Characteristics in Urban Street Canyons. *Journal of Applied Meteorology*, *38*, 1576-1589. https://doi.org/10.1175/1520-0450(1999)038<1576:ANSOFA>2.0.CO;2

Buccolieri, et al. (2009). Aerodynamic effects of trees on pollutant concentration in street canyons. *Science of the Total Environment*, *407*(19), 5247-5256. https://doi.org/https://doi.org/10.1016/j.scitotenv.2009.06.016

Buccolieri, et al. (2011). Analysis of local scale treeâ€“atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction. *Atmospheric Environment*, *45*(9), 1702-1713. https://doi.org/https://doi.org/10.1016/j.atmosenv.2010.12.058

Di Sabatino, et al. (2015). The effects of trees on micrometeorology in a real street canyon: consequences for local air quality. *International Journal of Environment and Pollution*, *58*(1/2), 100.

Garland, J. A. (2001). On the Size Dependence of Particle Deposition. *Water, Air and Soil Pollution: Focus*, *1*(5), 323-332. https://doi.org/10.1023/a:1013183911748

Gromke, C., Jamarkattel, N. & Ruck, B. (2016). Influence of roadside hedgerows on air quality in urban street canyons. *Atmospheric Environment*, *139*, 75-86. https://doi.org/https://doi.org/10.1016/j.atmosenv.2016.05.014

Gromke, C. & Ruck, B. (2012). Pollutant Concentrations in Street Canyons of Different Aspect Ratio with Avenues of Trees for Various Wind Directions. *Boundary-Layer Meteorology*, *144*(1), 41-64. https://doi.org/10.1007/s10546-012-9703-z

Hewitt, C. N., Ashworth, K. & MacKenzie, A. R. (2020). Using green infrastructure to improve urban air quality (GI4AQ). *Ambio*, *49*(1), 62-73. https://doi.org/10.1007/s13280-019-01164-3

Huang, et al. (2019). Effects of Wind Direction on the Airflow and Pollutant Dispersion inside a Long Street Canyon. *Aerosol and Air Quality Research*, *19*. https://doi.org/10.4209/aaqr.2018.09.0344

Hunter, L. J., Johnson, G. T. & Watson, I. D. (1992). An investigation of three-dimensional characteristics of flow regimes within the urban canyon. *Atmospheric Environment. Part B. Urban Atmosphere*, *26*(4), 425-432. https://doi.org/https://doi.org/10.1016/0957-1272(92)90049-X

Janhäll, S. (2015). Review on urban vegetation and particle air pollution – Deposition and dispersion. *Atmospheric Environment*, *105*, 130-137. https://doi.org/https://doi.org/10.1016/j.atmosenv.2015.01.052

Li, et al. (2016). The impacts of roadside vegetation barriers on the dispersion of gaseous traffic pollution in urban street canyons. *Urban Forestry & Urban Greening*, *17*, 80-91. https://doi.org/https://doi.org/10.1016/j.ufug.2016.03.006

Nazridoust, K. & Ahmadi, G. (2006). Airflow and pollutant transport in street canyons. *Journal of Wind Engineering and Industrial Aerodynamics*, *94*(6), 491-522. https://doi.org/https://doi.org/10.1016/j.jweia.2006.01.012

Niroobakhsh, A., Hassanzadeh, S. & Hoseinibalam, F. (2021). Flow and pollution concentration large-Eddy simulation and transition conditions for different street canyons and wind speeds: Environmental pollution reduction approach. *Urban Climate*, *35*, 100731. https://doi.org/https://doi.org/10.1016/j.uclim.2020.100731

Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and Buildings*, *11*(1), 103-113. https://doi.org/https://doi.org/10.1016/0378-7788(88)90026-6

Ries, K. & Eichhorn, J. (2001). *Simulation of effects of vegetation on the dispersion of pollutants in street canyons*. https://doi.org/10.1127/0941-2948/2001/0010-0229

Vardoulakis, et al. (2003). Modelling air quality in street canyons: a review. *Atmospheric Environment*, *37*(2), 155-182. https://doi.org/https://doi.org/10.1016/S1352-2310(02)00857-9

Vos, et al. (2013). Improving local air quality in cities: To tree or not to tree? *Environmental Pollution*, *144*(1), 41–64.

Vranckx, et al. (2015). Impact of trees on pollutant dispersion in street canyons: A numerical study of the annual average effects in Antwerp, Belgium. *Science of The Total Environment*, *532*, 474-483. https://doi.org/https://doi.org/10.1016/j.scitotenv.2015.06.032

Wang, et al. (2020). Effect of Street Canyon Shape and Tree Layout on Pollutant Diffusion under Real Tree Model. *Sustainability*, *12*(5).

Wania, et al. (2012). Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. *Journal of Environmental Management*, *94*(1), 91-101. https://doi.org/https://doi.org/10.1016/j.jenvman.2011.06.036

World Health Organization, W. (2022). *Ambient (outdoor) Air Pollution*. World Heath Organization. Retrieved 7 February 2023 from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Xie, et al. (2005). Thermal effects on vehicle emission dispersion in an urban street canyon. *Transportation Research Part D: Transport and Environment*, *10*(3), 197-212. https://doi.org/https://doi.org/10.1016/j.trd.2005.01.002

Xie, et al. (2007). Impact of building facades and ground heating on wind flow and pollutant transport in street canyons. *Atmospheric Environment*, *41*(39), 9030-9049. https://doi.org/https://doi.org/10.1016/j.atmosenv.2007.08.027

Yazid, et al. (2014). A review on the flow structure and pollutant dispersion in urban street canyons for urban planning strategies. *Simulation*, *90*. https://doi.org/10.1177/0037549714528046

Zhang, et al. (2015). Influence of Meteorological Conditions on Pollutant Dispersion in Street Canyon. *Procedia Engineering*, *121*, 899-905. https://doi.org/https://doi.org/10.1016/j.proeng.2015.09.047

Zhu, et al. (2022). The influence of roadside green belts and street canyon aspect ratios on air pollution dispersion and personal exposure. *Urban Climate*, *44*, 101236. https://doi.org/https://doi.org/10.1016/j.uclim.2022.101236

Cite as: Mogra S. & Khamidi M.F., Fadli F., “Theoretical Framework for Planning Urban Roadside Vegetation to Enhance Air Quality for Roadside Users”, *The 2nd International Conference on Civil Infrastructure and Construction (CIC 2023)*, Doha, Qatar, 5-8 February 2023, DOI: https://doi.org/10.29117/cic.2023.0137