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Urban nature-based solutions for particulate matter reduction and thermal comfort enhancement: empirical evidence from Guangdong Province

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Abstract. Rapid urbanization in warm and humid coastal regions has intensified exposure to particulate matter and outdoor heat stress, with significant implications for public health and energy demand. This article examines how urban nature-based solutions, including street trees, pocket parks, green roofs and integrated green corridors, influence particulate matter concentrations and outdoor thermal comfort in major cities of Guangdong Province. The study combines multi-year measurements from fixed and mobile monitoring stations with detailed urban morphology mapping and microclimate observations in representative street canyons, residential blocks and mixed-use districts. Thermal comfort is characterized using established human biometeorological indices, and particulate matter is measured at pedestrian height along paired nature-based solution and reference transects. Results indicate that well-designed nature-based solutions reduce daytime particulate matter concentrations by up to one third and lower mean radiant temperature by up to two degrees Celsius, with the largest benefits occurring in connected green corridors that combine shading and ventilation.

1 Introduction

Hea Urban regions in warm and humid climates face a dual challenge of high particulate matter exposure and persistent outdoor heat stress. Traffic emissions, industrial activity and dense building fabrics combine with background regional haze to elevate particulate concentrations, while extensive impervious surfaces and anthropogenic heat release intensify local air temperatures. These pressures are particularly acute in coastal provinces of southern China such as Guangdong, where rapid urban growth has transformed the Pearl River Delta into one of the world's largest continuous urbanized areas. In this context, conventional

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single-objective interventions that target either air quality or thermal comfort in isolation are unlikely to deliver durable improvements.

Nature-based solutions, understood as planned interventions that deploy vegetation, water and soil systems within urban fabrics, are increasingly promoted as a means of mitigating heat and improving air quality while providing co-benefits for biodiversity and liveability. Street trees, pocket parks, green roofs and integrated green corridors have the potential to cool the urban microclimate through shading and evapotranspiration and to intercept or dilute particulate matter at pedestrian level. However, the strength and direction of these effects depend on local climatic conditions, urban form and design details. In compact subtropical cities, poorly designed tree canopies may reduce ventilation in narrow street canyons, while isolated pockets of greenery may deliver only localized benefits.

The empirical evidence base for warm and humid Chinese cities remains relatively fragmented. Many existing studies rely on numerical simulations or short-term campaigns focused on thermal indicators, with less attention to simultaneous measurement of particulate matter and thermal comfort in real urban settings. Moreover, while there is a growing international literature on the role of urban green infrastructure in moderating heat and pollution, the transferability of results from temperate or arid climates to monsoonal, high-humidity environments is uncertain.

Jian Chai and Jing Fan review advanced thermal regulating materials and systems for buildings and show how phase change materials, dynamic facades and composite insulation can substantially improve indoor thermal comfort and reduce energy consumption in warm climates [1]. Aihua Wang, Jun Wang, Rui Zhang and Shanjun Cao focus on outdoor environments and develop an integrated framework that links green infrastructure and transport planning to the joint mitigation of urban heat and air pollution, highlighting the importance of street trees, roadside greenery and traffic management in densely built corridors [2].

Prabakaran Arumugam and Venkatesan Ramalingam demonstrate that phase change materials and enhanced insulation, when combined with natural ventilation, can significantly improve thermal comfort in office buildings under warm and humid conditions, underscoring the interplay between building envelope design and local climate [3]. Guoqiang Cui explores geometric optimisation of spaces around buildings and shows that courtyard orientation, aspect ratio and building spacing strongly influence thermal comfort efficiency in compact urban blocks [4]. Xin Zheng, Lei Chen and Jian Yang develop a simulation framework for early-stage design of urban streets that quantifies how streetscape geometry and vegetation affect outdoor thermal comfort and building energy use in summer [5].

Mladen Vujanović, Giovanni Besagni, Neven Duić and Christos Markides review innovations in thermal processes for production, storage, utilisation and conservation of energy, emphasising the synergies between thermal management technologies and broader sustainable engineering practices [6]. Djamel Belatrache, Sofiane Bentouba, Nabil Zioui and Mohamed Bourouis investigate the use of insulating materials derived from date palm waste in arid climates and report simultaneous gains in building energy efficiency and indoor comfort [7]. Qian He, Felipe Tapia and Alexandra Reith present a climate-specific review of nature-based solutions for reducing building cooling and heating energy demand and conclude that vegetation-based measures are particularly effective in warm climates with pronounced cooling loads [8]. Jing Ren, Jian Yang, Yu Zhang, Xinyue Xiao, Jiancheng Xia, Xinyan Li and Shuo Wang examine thermal comfort of urban buildings across local climate zones, illustrating the role of urban form classification in interpreting microclimatic data [9]. Hanna Oikarinen, Mikko Olin, Sanna Martikainen, Ville Leinonen, Simo Mikkonen and Pasi Karjalainen quantify particle number, mass and black carbon emissions from auxiliary heaters in real vehicle use, providing important reference values for urban particulate sources that nature-based solutions must counteract [10].

2 Material and methods

The empirical analysis covers three major urban agglomerations in Guangdong Province: the central Pearl River Delta, the eastern coastal belt and the western inland corridor. Within these areas, thirty-six observational sites were selected to represent a range of urban morphologies and nature-based solution typologies, including tree-lined boulevards, pocket parks embedded in residential blocks, extensive green roofs on commercial buildings and integrated riverfront green corridors. Each treated site was paired with a nearby reference location of similar built form and traffic intensity but with minimal vegetation, allowing a quasi-experimental comparison.

Particulate matter concentrations were monitored at pedestrian height using calibrated optical sensors co-located with regulatory monitoring stations for validation. Measurements were conducted at one-minute intervals and subsequently aggregated to hourly averages for the period 2019–2023, covering both dry and wet seasons. Microclimatic variables, including air temperature, relative humidity, wind speed, globe temperature and solar radiation, were recorded at the same locations. Thermal comfort was characterized using the Universal Thermal Climate Index, introduced with full calculation based on meteorological and radiation inputs and then used in abbreviated form as Universal Thermal Climate Index (UTCI) for analysis.

Land cover, tree canopy characteristics and building morphology were derived from high-resolution satellite imagery, airborne LIDAR and municipal geospatial databases. Vegetation structure was quantified using canopy cover percentage and leaf area index, while urban form metrics included building height, frontal area index and sky view factor. A mixed-methods analytical strategy was adopted. First, before and after comparisons were conducted for sites where nature-based solutions were implemented during the observation period. Second, cross-sectional comparisons between treated and reference sites controlled for meteorological variability using paired hours and multivariate regression. Third, hierarchical clustering of sites based on morphology and vegetation attributes was used to identify recurring combinations of urban form and nature-based solution typologies associated with favourable particulate and thermal comfort outcomes.

3 Results and discussion

The observational campaign reveals that nature-based solutions in Guangdong's warm and humid cities deliver measurable benefits for both particulate matter exposure and outdoor thermal comfort, although the magnitude and spatial extent of these benefits vary with urban form and design details. Street-level measurements show that tree-lined corridors and integrated green spaces reduce daytime particulate concentrations relative to nearby non-vegetated reference streets, especially during periods of high traffic and strong regional haze. At the same time, shaded areas exhibit lower mean radiant temperature and improved thermal comfort, with reductions most pronounced in locations where tree canopies are continuous and accompanied by permeable ground surfaces. However, the analysis also identifies conditions under which dense vegetation in narrow canyons can modestly increase particulate concentrations by suppressing vertical mixing, underscoring the importance of balancing shading and ventilation.

To disentangle these interactions, the study compares three representative nature-based solution configurations that are widely deployed in Guangdong's cities and for which multi-year before and after data are available: tree-lined arterial streets with continuous canopy cover, pocket parks embedded in high-rise residential complexes and integrated riverfront green corridors that combine riparian vegetation, shaded pathways and open lawns. For each configuration, changes in particulate matter concentration at pedestrian level, reductions in mean radiant temperature and changes in the proportion of daytime hours within a commonly used outdoor thermal comfort band are calculated relative to matched reference sites without significant greenery. Indicators are averaged over the main warm season from April to September for the years following implementation. The results are summarized in Table 1, which provides a compact overview of particulate and thermal benefits associated with each nature-based solution type, alongside a baseline for non-vegetated streets.

Table 1. Effects of urban nature-based solution typologies on particulate matter and thermal comfort indicators in warm seasons in Guangdong Province.

Site type and intervention status	**Reduction in daytime particulate matter concentration at pedestrian level (percent relative to reference)**	**Reduction in mean radiant temperature at 1.5 metres (degrees Celsius)**	**Increase in daytime hours within outdoor thermal comfort band (percentage points)**
Non-vegetated reference streets and plazas	0	0.0	0
Tree-lined arterial streets with continuous canopy cover	18	1.2	9
Pocket parks in high-rise residential complexes	24	1.5	14
Integrated riverfront green corridors with connected shade	32	2.0	21

The figures in Table 1 show that all three nature-based solution typologies deliver simultaneous improvements in particulate matter exposure and thermal comfort during the warm season relative to non-vegetated reference sites. Tree-lined arterial streets reduce daytime particulate concentrations at pedestrian level by an average of 18 percent and lower mean radiant temperature by 1.2 degrees Celsius, resulting in a nine percentage point increase in the share of daytime hours that fall within the outdoor thermal comfort band. Pocket parks embedded in high-rise residential complexes achieve larger average reductions in particulate matter of 24 percent and reduce mean radiant temperature by 1.5 degrees Celsius, increasing comfortable hours by 14 percentage points. Integrated riverfront green corridors perform best among the configurations studied, with particulate reductions of 32 percent, mean radiant temperature decreases of 2.0 degrees Celsius and an increase of 21 percentage points in daytime comfort hours. The gradient across typologies suggests that continuous, connected vegetation structures that combine shading, evapotranspiration and enhanced ventilation pathways, such as riverfront corridors, yield the greatest combined benefits, while linear tree plantings and isolated pockets provide more moderate but still meaningful improvements.

Beyond the average values reported in Table 1, temporal and spatial patterns reveal additional insights. The largest particulate matter reductions occur during late afternoon periods when sea breezes and convection enhance background ventilation; under these conditions, vegetation appears to act primarily as a surface that intercepts and filters particles rather than a barrier to dispersion. During stagnant morning rush hours, reductions are smaller and more variable, particularly in narrow canyons where dense tree canopies limit vertical exchange. In contrast, thermal comfort improvements are concentrated around midday and early afternoon, when shading and evapotranspiration most strongly offset high solar loads.

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Integrated riverfront corridors show relatively uniform benefits throughout the day, reflecting their openness to regional breezes and the combination of shade and open water effects.

Within residential complexes, pocket parks provide pronounced local cooling and particulate reduction but their influence decays rapidly beyond roughly fifty meters, highlighting the importance of spatial distribution and connectivity when planning such interventions at neighborhood scale. The combination of pocket parks with street trees along internal access roads extends the area over which comfort gains are realized and creates semi-continuous pathways of improved microclimate. Tree-lined arterial streets, while less effective than corridors and parks in absolute terms, have important strategic value because they coincide with high pedestrian flows and public transport access points, thereby delivering benefits to a large number of daily users.

The Guangdong results resonate with international evidence that well-designed nature-based solutions can moderate urban heat and improve air quality, but they also emphasize climate- and morphology-specific nuances. In the warm and humid monsoonal climate, shading emerges as a critical driver of thermal comfort improvement, while evapotranspiration benefits are attenuated by already high background humidity. For particulate matter, vegetation acts both as a sink and a flow modifier; design strategies that maintain adequate sky view factor and channel breezes along corridors appear to maximize net benefits. These findings have direct implications for urban planning in Guangdong and similar coastal megacities: nature-based solutions should be deployed not as isolated aesthetic interventions but as components of coherent green infrastructure networks aligned with prevailing wind patterns, street geometry and patterns of pedestrian exposure.

4 Conclusion

The empirical evidence from Guangdong Province demonstrates that urban nature-based solutions can deliver meaningful reductions in particulate matter exposure and substantial improvements in outdoor thermal comfort in warm and humid megacity environments. By combining multi-year particulate and microclimate measurements with detailed urban morphology mapping, the study quantifies the performance of tree-lined streets, pocket parks and integrated riverfront corridors relative to non-vegetated reference sites. The results show that continuous, connected green corridors offer the largest combined benefits, while linear tree plantings and small parks provide important but more localized improvements. These findings validate the practical value of nature-based solutions as part of broader strategies to reduce health risks from air pollution and heat in rapidly urbanizing coastal regions.

At the same time, the analysis highlights that benefits are not automatic and can be constrained by poor design. Dense canopies in narrow canyons may limit ventilation, and isolated green pockets may have limited reach beyond their immediate surroundings. The strong dependence of particulate and thermal outcomes on urban form and vegetation structure underscores the need for integrated planning that considers street geometry, building height, wind regimes and patterns of pedestrian movement. Limitations of the study include the focus on selected cities and typologies, the absence of explicit modelling of pollutant chemistry and the reliance on a single thermal comfort index.

Despite these constraints, the findings provide actionable guidance for planners in Guangdong and comparable warm and humid regions. Priority directions include the development of connected green corridors aligned with prevailing winds, the strategic placement of pocket parks in dense residential quarters and the coupling of tree planting programs with design guidelines that preserve ventilation. Future research should extend the empirical basis to additional pollutants, explore seasonal dynamics beyond the warm period and integrate economic and social evaluations to support equitable and scalable implementation of urban nature-based solutions.

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