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ORIGINAL PAPER

Coupling outdoor air quality with thermal comfort in the presence of street trees: a pilot investigation in Shenyang, Northeast China

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Abstract Together, the heat island effect and air pollution pose a threat to human health and well-being in urban settings. Nature-based solutions such as planting trees are a mitigation strategy to improve outdoor temperatures (thermal comfort) and enhance air quality in urban areas. In this study, outdoor thermal comfort, and particulate matter levels were compared between treeless and treed areas to provide a better understanding of how street trees improve thermal comfort and air quality. Street trees decreased the physiological equivalent temperature from 46.3 to 44.2 °C in summer but increased it from 36.4 to 37.5 °C in autumn. Air temperature and relative humidity contributed more in summer while wind speed contributed more in autumn. Particulate matter concentrations were negatively correlated with physiological equivalent temperature in summer but not in autumn. The presence of trees decreased concentrations of fine particulate matter in hot summer conditions but increased in hot autumn conditions. The presence of trees increased coarse particulate matter in very hot summer conditions in summer and in hot autumn conditions. Overall, the layout of trees in urban street canyons should consider the trade-off between outdoor thermal comfort and air quality improvement.

Keywords Air pollution · Particulate matter (PM) · Physiological equivalent temperature (PET) · Built environment · Urban design

Introduction

Urban areas occupy 3% of the planet's surface but support approximately 60% of the world's population (FAO 2020; Bonilla-Duarte et al. 2021). Rapid urban expansion is associated with environmental issues such as high temperatures and increased air pollution (Zhang et al. 2021). A high percentage of the global population is exposed to these environmental problems and increased summer temperatures and air pollutant concentrations increase the risk of premature mortality (Rodriguez-Algeciras et al. 2021). Therefore, mitigation strategies are necessary to improve outdoor thermal comfort and air quality in urban environments (Santiago and Rivas 2021).

Urban forests are a main mitigation strategy because of their environmental benefits such as pollution absorption, atmospheric cooling, reduced energy use and storm water mitigation (Pataki et al. 2021; Dong et al. 2022). The regulation of thermal comfort (outdoor temperatures) is an important benefit to mitigate the effect of urban heat islands effect, which refers to the increased surface

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temperature caused by the absorb and store solar radiation of pavements in the urban environments (Grylls and van Reeuwijk 2021). Tree canopies intercept solar radiation and their shade reduces mean radiant temperatures near the ground and decrease surface temperatures and heat storage (Grylls and van Reeuwijk 2021). They also provide cooling via transpiration that converts solar energy into latent heat, reduce net sensible heat flux and cools leaf surfaces and surrounding air (Santiago and Rivas 2021).

Another important benefit provided by urban forests is the improvement of air quality (Wolf et al. 2020). Urban forests change the dispersion, absorption, and deposition of air pollutants (Santiago and Rivas 2021). Air pollutants can enter intercellular leaf spaces through stomata and are absorbed by water films to form acids or react with internal leaf surfaces (Santiago and Rivas 2021). Pollutants can also be intercepted and stored on leaf and trunk surfaces to reduce their concentration in the air (Bonilla-Duarte et al. 2021). The effects of absorption and deposition on air quality are always positive; however, aerodynamics can be positive or negative, depending on the urban forest structure and environmental factors (Santiago and Rivas 2021). The structure and spatial configuration of trees in built-up environments changes wind velocity and produces local inversions to trap pollutants and thus increases local air pollutant concentration (Cavanagh et al. 2009). However, the net influence of urban forests on air pollutants that result from dispersion, absorption and deposition processes is still unknown.

The influence of urban forests on air pollutant concentrations is related to their regulation of thermal comfort or outdoor temperatures. Transpiration and shading by trees reduce local air temperatures, increase relative humidity, and promote the deposition of proximate particles onto plant surfaces (Chen et al. 2016; Ryu et al. 2019; Zhu et al. 2019). Cooler air temperatures provided by trees also reduce the rate of photochemical reactions and decrease ozone concentrations (Cavanagh et al. 2009). However, trees may increase pollutant concentrations by releasing volatile organic compounds that react with nitrogen oxides and produce additional ozone (Cavanagh et al. 2009).

Although previous studies have investigated the air pollutant removal and thermal effects of trees, three issues remain: (1) most studies have been conducted using idealized tree configurations based on either numerical simulations or wind tunnel tests (Miao et al. 2021). The air purification of street trees in real street canyons remains unclear; (2) previous research has mainly focused on decreases in air temperature and increases in relative humidity in the presence of trees but their influence on outdoor thermal comfort is not well understood (Ren et al. 2022); and, (3) the regulation by urban forests of both air quality and outdoor thermal comfort and their interaction remains unclear.

To address these research gaps, a field investigation was carried out to explore the influence of street trees on outdoor thermal comfort and air quality. The association between thermal comfort and air pollutant concentrations was also examined to promote collaborative mitigation strategies. This study relates outdoor air quality to thermal comfort in the presence of street trees based on a field investigation. Outdoor thermal comfort, air quality and their association in the presence of street trees were assessed and analyzed based on the results and published research.

Materials and methods

Study site

The study was in Shenyang (41°48′11.75″ N, 123°25′31.18″ E), the capital of Liaoning Province, China. The city has a population of approximately 8.3 million and covers an area of almost 13,000 km^2. It has a mid-temperate, continental climate with four distinct seasons. It is hot and humid in summer, cold and dry in winter, and rapid temperature changes in spring and autumn. Average annual temperature is 8.4 °C, with a maximum of 24.7 °C in July. Average annual rainfall is 510–680 mm, most of which falls in July and August. In 2020, Shenyang recorded serious air pollution on 79 days, and on almost 60% of the pollution days, the primary pollutant was $PM_{2.5}$ (particulate matter with diameter less than 2.5 μm) (Liaoning Shenyang Ecological Environment Monitoring Center 2021).

Five streets with planted trees were selected to compare outdoor thermal comfort and particulate matter (PM) concentrations between points with and without trees (Fig. 1). Observation points without trees were used as controls to assess the influence of street trees on air quality and outdoor thermal comfort. All five sites were chosen with sections with planted and without planted trees on the same side of the street with similar building heights to ensure similar airflow and solar radiation at the two points. The species of trees planted in these streets were *Sophora japonica* L., *Populus alba* L., and *Ulmus pumila* L.

Data collection

Measurements of particulate matter concentrations and microclimatic factors were carried out over five days in summer and five days in the autumn in 2020. Measurements were taken at 1.5 m above the street between 14:00 and 19:00 local time. The observations were taken at an average breathing height (1.5 m) to assess the direct feeling of thermal comfort and exposure to air pollution.

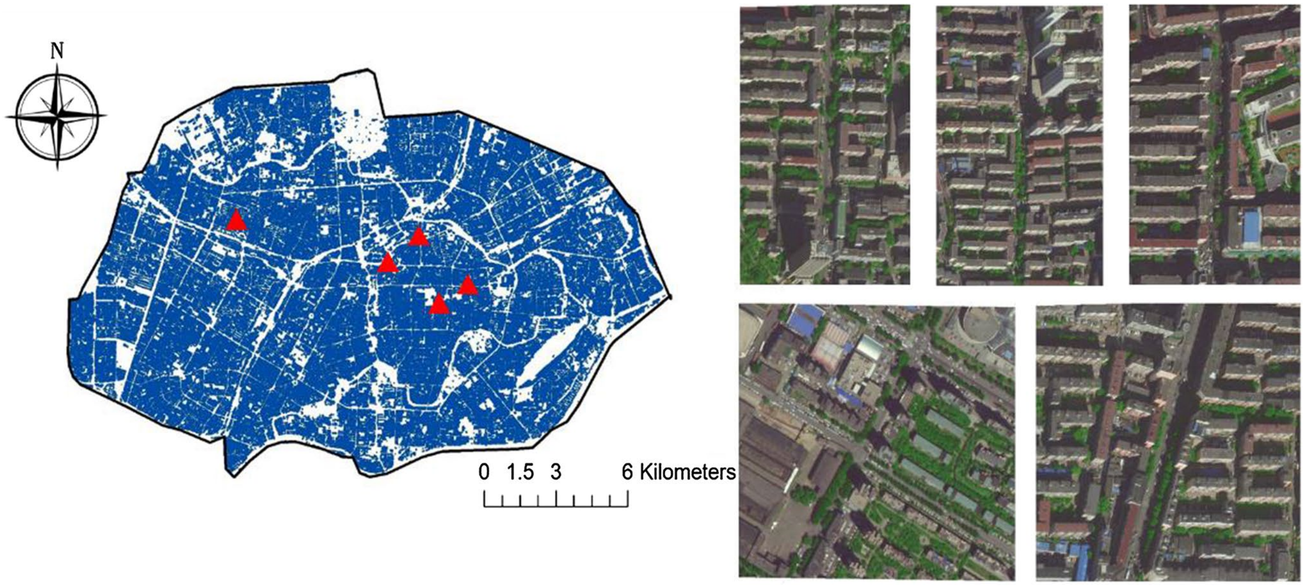

Fig. 1 Observation sites in the community areas inside the second ring of Shenyang

PM_1 (PM with diameter less than 1 µm), $PM_{2.5}$, PM_4 (PM with diameter less than 4 µm), PM_{10} (PM with diameter less than 10 µm), and TSP (total suspended particles) concentrations were collected at one minute intervals using an AEROCET 831 (Met One Instruments, Inc., a registered ISO 9001 company, 1600 NW Washington Blvd, Grants Pass, OR 97,526, USA) with an accuracy of ± 10%. The AEROCET 831 measures distribution of particle size and converts them to particulate concentrations using a proprietary algorithm. Microclimatic factors, including wind speed and direction, air temperature, relative humidity, and atmospheric pressure, were recorded using a TNHY-5-A-G meteorological parameter instrument (Zhejiang Top Cloud-Agri Technology Co. Ltd., China) at five-minute intervals.

The physiological equivalent temperature (PET) is defined as: "the air temperature at which the human body's energy budget under conditions free of wind and solar radiation is balanced with its core and skin temperature in the relevant outdoor environment to be assessed". It is widely used to evaluate outdoor thermal comfort because it is free of behavioral components and describes the thermo-physiological condition. In this study, PET was calculated in a Rayman Pro model using inputs of wind speed, air temperature, relative humidity, and the individual's data (a 35 year-old man, weight 75 kg, height 1.7 m, activity 80 W, clothing 0.9 clo) (Rodriguez-Algeciras et al. 2021). The thermal perception was divided into slightly warm (23 – 29 °C), warm (29 – 35 °C), hot (35 – 41 °C) and very hot (> 41 °C), according to the PET value (Matzarakis et al. 1999).

Data analysis

The differences in the physiological equivalent temperature, air temperature, relative humidity, wind speed and particulate matter (PM) concentrations between areas without trees and with trees were assessed using a student's t-test in summer and autumn, respectively. PM concentrations at different perceptions of thermal comfort were also assessed in this manner in the SPSS statistical package for windows 18.0 (SPSS Inc., Chicago, IL, USA). The pairwise Pearson correlation between pairs of PM concentrations, air temperature, relative humidity, wind speed, wind direction, atmospheric pressure and PET was calculated to explore their association (Eslami and Saeed 2018). The differences in Pearson's correlation and t-test were considered significant at $p < 0.05$.

Results

Outdoor thermal comfort

Figure 2 shows the microclimatic factors and PET differences between treeless and treed areas in summer and autumn. With trees, air temperature decreased from (34.8 ± 0.3) °C to (31.9 ± 0.2) °C in summer, and from (23.3 ± 0.2) °C to (22.4 ± 0.1) °C in autumn. Relative humidity increased from 44.7% to 56.8% in summer, and from 51.2% to 56.8% in autumn. Wind speeds in treeless areas were 1.3 and 0.6 m s^{-1} in summer and autumn, respectively, both significantly higher than those in treed areas. PET values decreased from (46.3 ± 0.4) °C to (44.2 ± 0.4) °C in

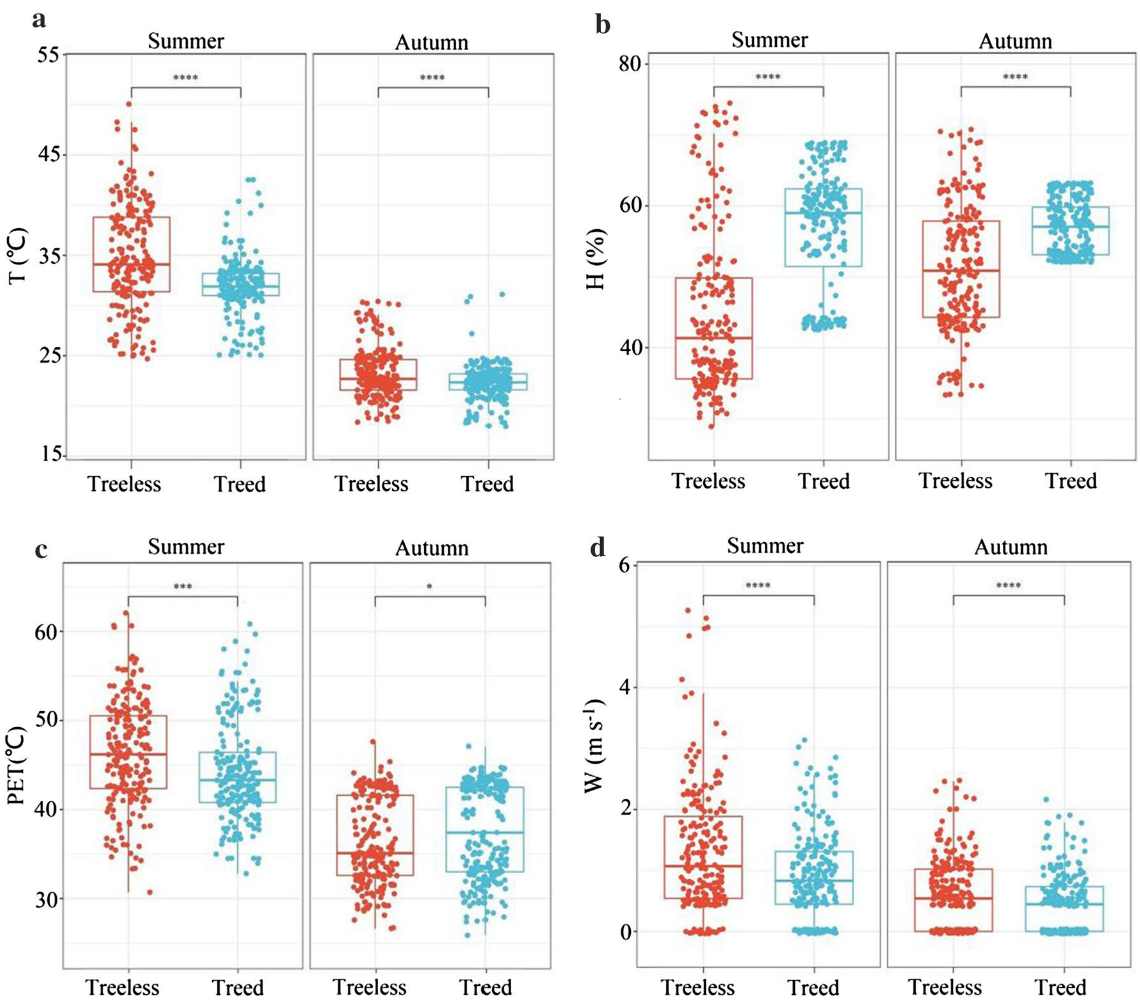

Fig. 2 Air temperature (T), relative humidity (H), PET and wind speed (W) in treeless and treed areas in summer and autumn

summer but increased from (36.4 ± 0.3) °C to (37.5 ± 0.4) °C in autumn on treed streets.

PM concentrations in treed areas.

The difference in PM concentrations in the presence of trees varied with particle size (Fig. 3). No significant difference was found between treeless and treed areas in either summer or autumn for fine particles PM_1, $PM_{2.5}$ and PM_4. However, significantly higher PM_{10} and TSP levels were found in the presence of trees in both summer and autumn. PM_{10} concentrations increased from 72.8 ± 3.0 to 86.0 ± 3.4 μg m^{-3} in summer, and from 63.6 ± 2.9 to 77.8 ± 2.5 μg m^{-3} in autumn. TSP concentrations increased from 91.3 ± 3.7 to 106.2 ± 3.6 μg m^{-3} in summer and from 80.2 ± 3.4 to 101.3 ± 3.6 μg m^{-3} in autumn. The differences in PM concentrations between summer and autumn decreased as particle size increased.

Association between outdoor thermal comfort and particulate matter levels

Pairwise Pearson's correlation heatmaps were developed to explore the association between pair of PM concentrations, air temperatures, relative humidity, wind speeds, wind direction, atmospheric pressure and PET in summer and autumn (Fig. 4). According to the correlation coefficients shown in the heatmaps, there were significant negative correlations between PET and PM concentrations; only fine particulate matter had a significant positive correlation with outdoor thermal comfort in autumn. The correlations between PET and PM concentrations in summer and in autumn decreased on streets with trees. In summer, the correlation between PET, air temperature, and relative humidity decreased, but increased between PET and wind speed. In autumn, the correlations between PET, air temperature, and wind speed increased, whereas the correlation between PET and relative humidity decreased in

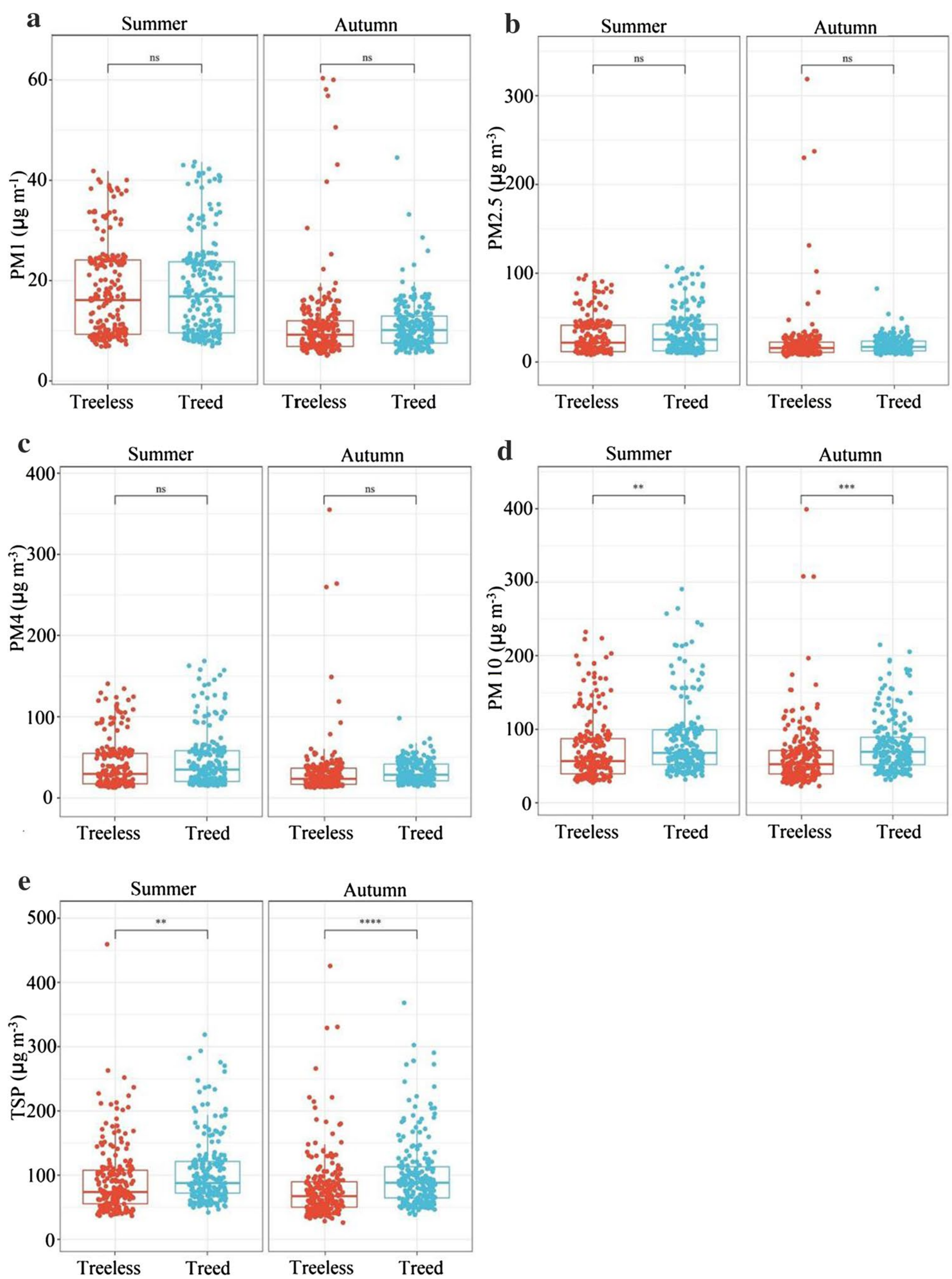

Fig. 3 PM concentrations in treeless and treed areas in summer and autumn

treed areas. In addition, the correlations between PM concentrations and wind speed in both summer and autumn decreased with trees.

To further understand the association between particulate matter levels and thermal comfort, PM concentrations in treeless and treed areas were compared in slightly warm, warm, hot, and very hot conditions (Fig. 5). The difference in PM concentrations with trees varied with thermal perception. Fine particles (PM_1, $PM_{2.5}$) decreased in the presence of trees in hot conditions, whereas coarse particles (PM_{10}, TSP) increased in warm and very hot conditions in summer. In autumn, trees increased fine particle concentrations under hot conditions and increased coarse particles under both warm and hot conditions.

Discussion

Outdoor thermal comfort

The positive influence of urban forests on outdoor thermal comfort results from their cooling effect through shade and transpiration (Rahman et al. 2020; Richards et al. 2020). Shading and evapotranspiration lead to an increase in

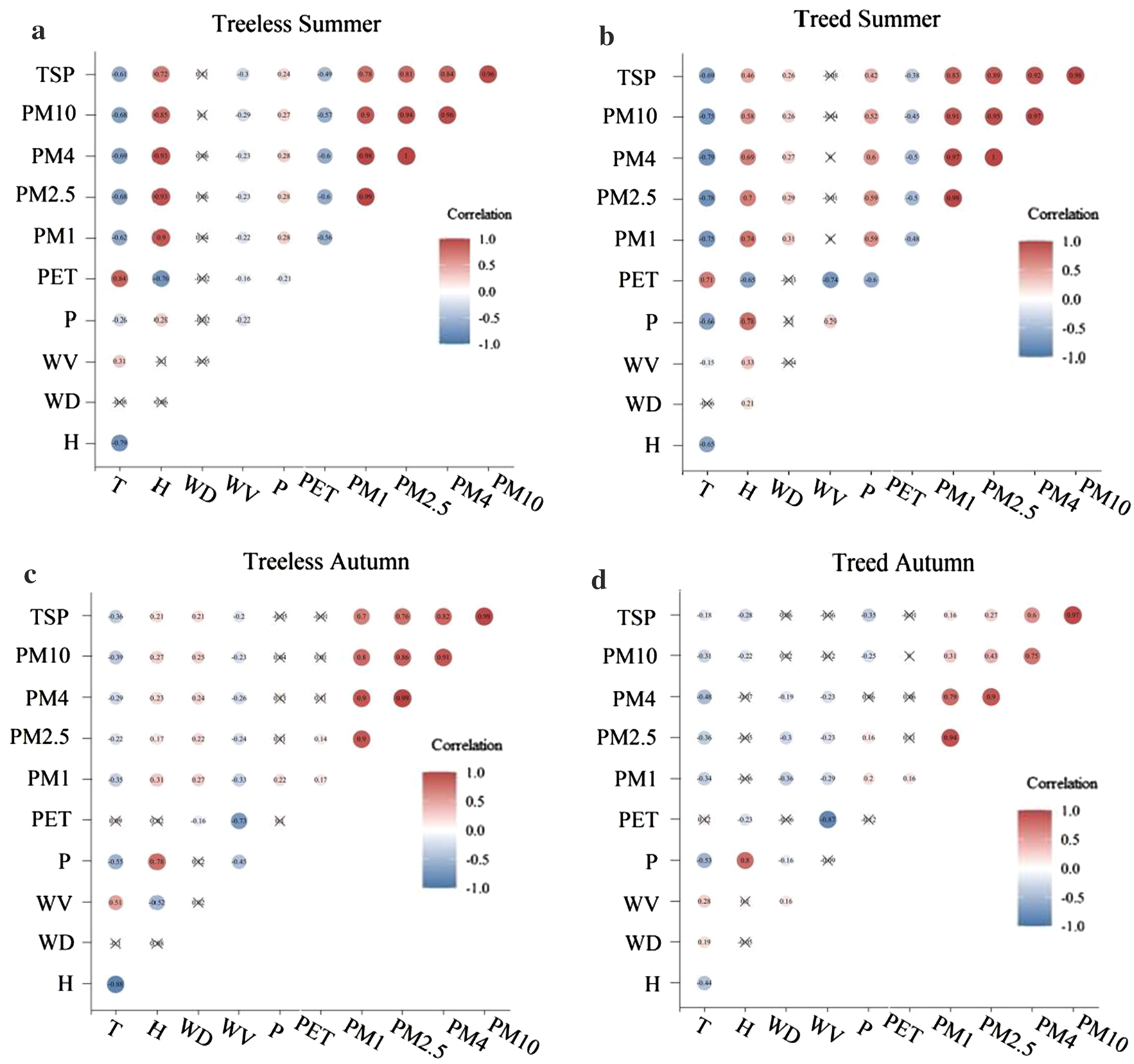

Fig. 4 Pearson's correlation between air temperature (T), relative humidity (H), PET, wind speed, and PM concentration in treeless and treed areas in summer and autumn

relative humidity and a reduction in air temperatures (Ren et al. 2022). In this study, the results show the positive influence on air temperature mitigation and the increase in relative humidity, which agree with Gatto et al. (2020). Approximately 3 °C and 1 °C decrease in temperature was found on treed streets in summer and autumn, respectively. The 12.0% and 5.5% increase in relative humidity was also recorded with trees in summer and autumn, respectively (Fig. 2). Wind speeds in both summer and in autumn decreased in the presence of trees. The change in temperatures, relative humidity and wind speed contributed to the change in physiological equivalent temperature (PET).

With trees, PET decreased by 2.0 °C under very hot conditions (summer) but increased by 1.1 °C in autumn. In summer, PET was correlated with air temperature and relative humidity (Fig. 4). The improvement in thermal comfort in summer benefited from the decrease in temperature and the increase in relative humidity. Wind speed had no significant correlation with PET (Fig. 2). In terms of outdoor thermal comfort, wind speed has less effect than cooling caused by trees in summer (Jeong et al. 2016). Compared with summer, PET in the autumn was more negatively correlated with wind speed but less with temperature and relative humidity (Fig. 2). The slight increase in PET in autumn resulted from the decrease in wind speed in the presence of trees. The difference in PET with trees between summer and autumn is possibly due to differences in background temperatures. Trees improve thermal comfort more in conditions with higher temperatures (Ren et al. 2022).

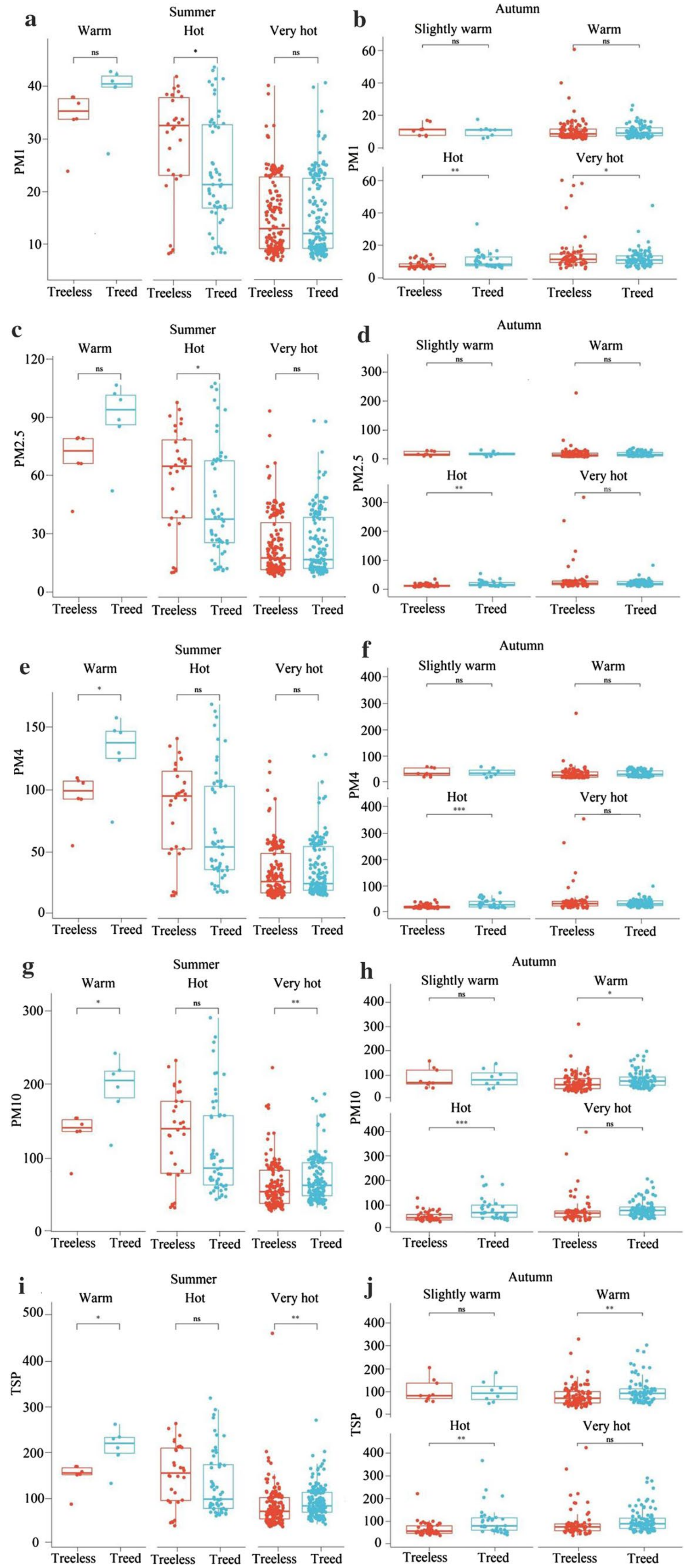

Fig. 5 PM concentrations at different levels of thermal comfort in both treeless and treed areas in summer and autumn

Air quality and its association with thermal comfort

PM concentrations showed a similar trend in the presence of trees in summer and autumn (Fig. 3). There was no significant difference in PM_1, $PM_{2.5}$ and PM_4 concentrations between treeless and treed areas, whereas higher PM_{10} and TSP levels were found in areas with trees. Therefore, the influence of trees, especially in a built environment, was not always positive (Abhijith et al. 2017). Some studies have reported negative effects from tree planting on air quality (Abhijith and Gokhale 2015; Yang et al. 2020). The increase in the particulate matter levels in treed areas is probably due to their aerodynamic effect (Miao et al. 2021)The aerodynamic effect on the dispersion of air pollutants was stronger than the positive deposition in the presence of trees (Vos et al. 2013; Jeanjean et al. 2017).

The PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP concentrations were significantly negatively correlated with PET in summer, whereas the PM_1 and $PM_{2.5}$ levels were positively in autumn (Fig. 4). This indicates that PM concentrations increased as thermal comfort improved in summer. Thermal comfort was more closely related to relative humidity than to wind speed as discussed above. The increased relative humidity improved thermal comfort but promoted PM collision and coalescence, and thus increased their concentrations in summer (Miao et al. 2020). Particulate matter levels were significantly and positively correlated with relative humidity but negatively correlated with air temperature in summer (Fig. 4). In autumn, correlations between PM concentrations, air temperatures, and relative humidity decreased and the correlation with PET also decreased. The difference in correlation between two seasons is possibly due to the background difference in air temperature, relative humidity, and PET values (Miao et al. 2021; Ren et al. 2022).

PM concentrations were significantly correlated with PET, and therefore the impact of trees on PM concentration varied with thermal perception and with the season (Fig. 5). Coarse PM concentrations significantly increased in the presence of trees in very hot conditions, while there was no significant difference under hot conditions in summer. The correlation was reversed in autumn. Trees decreased fine PM levels under hot conditions in summer, whereas they increased in autumn. The increase in coarse PM concentrations and decrease in fine particulate matter in the presence of trees can be explained by the processes of deposition and dispersion (Huang et al. 2021). Coarse PM tends to remain on tree surfaces whereas fine PM is more easily dispersed from the canopy (Janhall 2015).

Conclusion

Mitigating air pollution and improving thermal comfort are two of the most important ecosystem services provided by urban forests and are closely related to human well-being. In this study, outdoor thermal comfort, air quality, and the association between them were explored in treeless and treed areas in the summer and autumn of 2020. The PET (physiological equivalent temperature) in treeless areas was 2 °C higher than in treed areas in summer but approximately 1 °C lower in autumn. Air temperature and relative humidity significantly affected PET in summer, whereas wind speed had a greater effect in autumn. Particulate matter levels had a negative correlation with PET in summer, but it was insignificant in autumn. Coarse particulate matter in treed areas was much higher than in treeless areas in very hot conditions in summer; a similar trend was shown in autumn. Fine particulate concentrations areas with trees were significantly lower than in treeless areas in hot summer conditions and vice versa in autumn. The correlation between air quality and thermal comfort was related to the background air temperature, relative humidity, and PET values. The findings show that well-designed and sustainable management of urban street trees will help promote healthy lives and well-being of the communities and improve the environmental footprint of urban areas.

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