Assessment of Seasonal and Vegetational Variations in the Airborne Bacterial Concentration of the Urban Forest Park: A Case Study in Hunan, China

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Abstract

It is important to investigate bacterial air quality in urban forest parks because tree bacteriostasis practices are being increasingly advocated as measures to improve the air quality and public-health in urban green spaces around the world. The aim of the present study was to quantitatively investigate airborne bacterial concentration levels based on field measurements in every season in five selected forest communities and the uncovered space in an urban forest park, as well as the effects of several factors on the culturability of airborne bacteria. Results suggested that the airborne bacterial levels of all forest communities reached the clean air quality standard with regard to the airborne bacteria content, with the highest bacteria concentrations in the uncovered space (1658 ± 1298 CFU/m³), and the lowest in the mixed community (907 ± 567 CFU/m³). The temporal distribution analysis showed that the most airborne bacteria were concentrated in summer, as well as in the morning and afternoon. The bacteriostatic rates of the mixed community were significantly different with seasonal variation ($p < 0.05$). Spearman's correlations revealed that the bacterial concentration was significantly positively correlated with the season, wind speed (WS), temperature (T), ultraviolet light (UV), negative air ion (NAI) and total suspended particles (TSP) ($p \leq 0.05$), but significantly negatively correlated with the forest community type ($p < 0.05$). WS, UV, NAI, TSP and PM_{2.5} showed significant effect on airborne bacterial concentration in a multiple linear regression model ($p < 0.05$). Overall, the selection of tree species plays a key role in shaping the forest structure and improving air quality, and the urban forest highlights key priorities for future efforts towards a cleaner, healthier, and more diverse regional forest environment.

Introduction

With rapid social development and urbanization processes, human health risks increase due to lifestyle-related stress and surrounding environment deterioration, and the amount of pathogenic bacteria related to human diseases in the air keep increasing. Since the development of the concept of "forest bath" as a therapy in the 2000s, many studies using a variety of methodologies, have been conducted to verify the effect of forest environments on encouraging physical recreation and promoting physiological restoration (Bielinis et al. 2018; Joung et al. 2015; Ochiai et al. 2015; Song et al. 2017; Yu and Hsieh 2020). The assessment of the various environmental factors (airborne microbes, biogenic volatile organic compounds (BVOCs), negative air ion (NAI), air pollutants, particulate matter (Broeckx et al.), and etc.) of the forest park represent one of the biggest concerns for public health (Guo et al. 2013; Jiang et al. 2018; Li et al. 2019; Zhao et al. 2018). Furthermore, the airborne bacteria, as an important component of airborne microbes, depends on the type, range, plant species and crown density of green space (Ren et al. 2012). Urban forest parks are the main areas for people to recreation and healthcare in the daily life (Oh et al. 2017). It is therefore necessary to explore the changing airborne bacteria of different forest communities and related influence factors.

The previous studies on airborne bacterial distribution and concentration have been conducted within the maximum human exposure range, such as residences, school, hospitals, industrial regions, and parks (Chegini et al. 2020; Gao et al. 2018; Guan et al. 2015; Harbizadeh et al. 2019; Hui et al. 2019; Ye et al. 2021). Abundant studies have suggested lower bacterial concentrations outdoors (Hui et al. 2019). Regarding to outdoor air, it has been reported that the amount of bacterial colony in the forests might be 100 times lower than that of urban areas air or rather less (Fang et al. 2007; Huang and Wu 2002; Mu et al. 2020). In addition, Dong et al. (2018) demonstrated that the airborne bacterial content was in ascending order as arboreous forest, shrub forest, herb community. Furthermore, different plant species also significantly impact the ambient bacterial concentrations. Study has shown that the airborne bacterial concentration of needle-leaved trees were higher than broad-leaved trees (Gu et al. 2020). On the other hand, with the increase in altitude or distance, airborne bacterial concentrations vary in one forest community. Lyngwi et al. (2013) pointed out that bacterial concentrations of tropical Eastern Himalaya which decreased with increasing altitudes. A study found that the horizontal change of airborne bacterial concentrations was on descend trend within 15m distance of the border of urban green areas, and no significant difference beyond the 15m (Ren 2007). The abovementioned studies indicated relatively large changes in airborne bacterial concentration associated with the specific locations, and these changes follow a pattern for each season (spring, summer, autumn and winter) of the year according to region (Gandolfi et al. 2015; Li et al. 2019). In the subtropical cities of China, the bacterial concentrations between spring and winter and temperate climates varied by three and one order of magnitude, respectively (Xie et al. 2019). As airborne bacteria present everywhere in indoor and outdoor environments, the variations of bacterial concentrations could mainly be explained by region and time.

However, recent studies have indicated strong evidence that airborne bacteria can also be affected by environmental factors, such as temperature (T), wind speed (WS), relative humidity (RH), PM_{2.5}, PM₁₀, SO₂ (Gao et al. 2015; Jones and Harrison 2004; Li et al. 2019; Li et al. 2021; Ruiz-Gil et al. 2020; Zhong et al. 2016). Airborne bacteria as an important biological component of forest ecosystem, the forest community-transfer of environmental bacteria is more likely affected by the forest microclimate conditions including T, RH, WS (Amini Parsa et al. 2019; Boehnke et al. 2017). The contents of airborne bacteria significantly increased with the air temperature increasing from 10 °C to 15 °C in spring (Gu et al. 2020). While a growing number of studies focusing on the dust detaining abilities of different trees were conducted in various environments (Mcdonald et al. 2007; Nowak et al. 2006; Song et al. 2015), there is still a lack of studies that assess the correlation among airborne bacteria, forest community type, meteorological elements and particulate matter in the forest (Guo et al. 2013).

The urban forest park is a place where people often relax and exercise (Meyer et al. 2019). Hence, due to the diverse vegetational species, the complex internal environment and the various ecological function of the urban forest park, it is meaningful to investigate its bacterial air quality. In this study, we provided firsthand information concerning airborne bacteria in an urban forest park. As such, the aim of this study was to investigate the seasonal and temporal variations of airborne bacterial concentration and antimicrobial capacity of different vegetation types in urban green areas, and figure out the driving factors of airborne bacterial concentrations. The research results are of great significance to make decisions of the construction and management of forest healthcare, which would improve human health and well-being by making the urban environment a more pleasant and aesthetic place to live.

Materials And Methods

Description of sampling sites

This study was conducted in an urban botanical garden (25.78° N, 112.99° E) located in the western part of Chenzhou City in the southeast of Hunan Province, China (Fig. 1). Nanling botanical garden has a total area of 0.402 km², and its altitude ranges from 120 to 338 m. It belongs to the subtropical monsoon humid climate zone. The local climate experiences long summers and short winters, and is hot and humid. The annual average temperature is 17.4 °C, and the annual precipitation is 1452.1 mm. The frost-free period is 284 days per year.

There are various types of vegetation, and a total of 6 sampling sites (based on forest community type) were selected, as presented in Table 1. The blank plots were selected to be in the square (an open space), and had no vegetation. The sampling plots inside the forest which included deciduous broad-leaved community, evergreen broad-leaved community, deciduous needle-leaf community, evergreen coniferous community, mixed needle-leaf and broad-leaved community and uncovered space.

Airborne bacteria collection and analysis

The ambient air samplings of different forest community types were conducted at 2 h intervals during the daytime from 8 am to 6 pm in January 2020 (winter), April 2020 (spring), August 2020 (summer), and November 2020 (autumn). Samples from each site during each season had been collected with sunny for at least three consecutive days and there was little rain or cloud cover. Three sampling points were set in every forest plot by the diagonal method.

The airborne bacteria were collected with disposable petri dishes (90 × 90mm, size) using Nutrient Agar (Shengsi Bio Tech, Inc., Shanghai, China) as the culture medium, where microbial partimhcles settlement onto these agar mediums by gravity. Triplicate samples disposable petri dishes from each sampling location, approximately 1.2–1.5 m above ground level (being close to human breathing height), were collected airborne bacteria for 10 min duration. Thus, airborne bacteria emission rates of each forest plot were calculated by averaging 9 values (3 locations × 3 plates). Nutrient Agar was prepared for bacteria by using 33g of agar per liter. Mediums were previously prepared and sterilized in the autoclave (YXQ-LS-75S11, Boxun Industry&Commerce Co. Ltd., ShangHai, China) before pouring it in petri dishes.

After collection, the sampled petri dishes should be inverted and sealed up immediately, then brought back to the laboratory and cultured in a constant temperature incubator (ZXSD-B1270,Zhicheng instrument Corp., ShangHai, China). The bacteria were incubated at 37 °C for 48 h. The concentrations were expressed as colony-forming units per cubic meter of air (CFU/m³). For each forest community sampling site, the air sampler was always wiped with alcohol between sample collections to avoid cross-contamination. Three field blanks were assessed for every forest community and no field blank samples were positive.

The colonies obtained were expressed as CFU/m³. The airborne bacterial concentration was calculated by using Eq. (1) (Zhou et al. 2010).

$$C = \frac{5000 \times N}{A \times t} \quad (1)$$

In Eq. (1), C (CFU/m³) is the concentration of bacteria in the air, N (CFU) is the total number of colonies, t (min) is the sampling time, and A (cm²) is the petri dish's area.

The bacteriostatic rate expressed as % were calculated by Eq. (2) (Zhou et al. 2010).

$$Y = \frac{(E_i - E_j) \times 100}{E_j} \quad (2)$$

In Eq. (2), Y (%) is the bacteriostatic rate of the sampling site, E_j (CFU/m³) is the airborne bacterial concentrations of the sampling site of CK, E_i (CFU/m³) is the airborne bacterial concentrations of the sampling site inside the forest.

Environmental factor measurements

Concurrently, the forest environment, including wind speed (WS), relative humidity (RH), temperature (T), ultraviolet light (UV), negative air ion (NAI) and particulate matter (PM) concentrations [total suspended particles (TSP), PM10, PM2.5, PM1.0] of each forest plot were measured while sampling airborne bacteria. Kestrel Weather Meter (Kestrel 5500, Nielsen-Kellerman Co., USA) was employed to record the T, RH and WS (T: -29-70 °C (range), ± 0.1°C (accuracy); RH: 0-99.9% (range), ± 0.1% (accuracy); WS: 0–40.0 m/s (range), ± 0.1 m/s (accuracy)). UV was measured by a Dual-channel UV meter with a 254 detector (UV-B, Beijing Shida Photoelectric Technology Ltd., China), λ_p from 230 to 275 nm, and the measuring range of the detector was 0.1-199.9×10³ μW/cm², the operating T and humidity were 0–40 °C and 85% RH. NAI concentration was measured by a unified corrected negative ion monitor COM-3200PRO II produced in Japan with an observation range of the detector was 10–1.999*10⁹ ion/cm³, the operating T and humidity were 4–40 °C and 100% RH. The Turnkey DustMate environment monitor (DUSTMATE, Turnkey Instruments Ltd, UK) was used to measure TSP (0.1 μg/m³ accuracy), PM10 (0.1 μg/m³ accuracy), PM2.5 (0.01 μg/m³ accuracy), PM1.0 (0.01 μg/m³ accuracy) mass concentration with a range of 0.01–6000 μg/m³. All instruments have been calibrated before sampling.

Data analysis

The data were analysed using Origin 2021 (OriginLab, USA) and SPSS 23.0 (IBM Corp., USA). As the distribution was parametric, one-way ANOVA was used to compare airborne bacterial concentrations among different forest community types and the bacteriostatic rate of forest community types from the spring to winter. The t-test was used to analyze the significant difference in the comparison of the forest community types for the same season of bacteriostatic rate. In addition, the relationships among bacteria, meteorological factors, and air pollutants were examined using non-parametric Spearman's rank correlation

method. A multiple linear regression model was used to analyze the effects of several variables (T, RH, WS, UV, NAI, TSP, PM10, PM2.5 and PM1.0) on airborne bacterial concentrations. Statistical significance was defined as $p < 0.05$.

Results And Discussion

Distribution characteristics of airborne bacterial concentration

Vegetational variation in airborne bacterial concentration

The airborne bacterial samples were collected from the five forest communities and an uncovered space environment, and the concentrations of airborne bacteria are illustrated in Fig. 2. Considering the five forest communities, the whole year of airborne bacterial concentrations varied greatly, and from least to highest was SA < SM < SN $\approx$ SK < ST, the averages were 907 ± 567 , 1067 ± 736 , 1157 ± 770 , 1120 ± 693 and 1364 ± 882 CFU/m³, respectively. The average airborne bacterial concentration of the mixed forest was the least, which was significant lower than that of CK ($p < 0.05$). The two kinds of evergreen forests were found to be less than those of deciduous, and the broad-leaved forests were also found to be less than those of needle-leaved trees. Gu et al. (2020) studied airborne bacterial concentration of three forest communities (Chinese fir (*Cunninghamia lanceolata*), masson pine (*Pinus massoniana*) and moso bamboo (*Phyllostachys pubescens*)) in China, and found that moso bamboo (broad-leaved trees) had lower airborne bacterial concentration than Chinese fir and masson pine (needle-leaved trees), which is similar to our results. The airborne bacterial concentration of CK was the highest with the average of 1658 CFU/m³. The findings revealed that the average concentration of the airborne bacteria in the urban forest park was lower than the recommended value of the air-quality standard of China (< 2500 CFU/m³) (China, 2002), indicating the range of cleaner to clean. The concentration of airborne bacteria in the urban forest space was less than that found in the studies performed in the Xi'an downtown region ($0.83 \pm 0.45 \times 10^5$ cells/m³) (Bai et al. 2021), or the outside of Nanjing Forestry University (4596 CFU/m³) (Liu 2006), but was higher than the 87 CFU/m³ measured in a remote forest mountain in China (Gu et al. 2020). Different studies have found that the airborne bacterial concentration significantly differed across different areas, which may be because of different environmental conditions, the difference in the nature of activities and specific sources (Maki et al. 2017; Zhai et al. 2018). This demonstrates that people living in urban environments are exposed to a higher bacterial concentration compared to rural inhabitants.

Temporal variability in airborne bacterial concentrations

In this study, temporal variations of airborne bacterial concentration of all tested forest communities during the sampling period over the four seasons are shown in Fig. 3.

From the perspective of the whole year, the seasonal average change trend of airborne bacterial concentration of urban forest in spring and summer were higher than these in autumn and winter, and summer was the highest concentration over seasons. Additionally, the airborne bacterial concentrations of all sampling forest communities showed a similar trend, that is, a greater concentration in the late morning and early afternoon than in the early morning and late afternoon or at noon. Interestingly, while the trend is generally M-shaped, it is sometimes not obvious, this may be due to external factors, such as human, plants and animals activities. This suggests that the concentration of airborne bacteria increased with increasing activities from human or other living organism, which consistent with the hypothesis of biological circadian rhythms (Heo et al. 2017). What's more, in winter, the airborne bacterial concentrations of all forest sampling sites were higher than CK at noon, especially significantly higher in SA ($p < 0.01$), and increased as temperature increased between 12:00 and 16:00. The airborne bacteria daily bottom hours were at the sampling time of 18:00 in spring, CK, SN, SM, ST, and SK, the concentrations of airborne bacteria were 594 ± 264 , 838 ± 105 , 419 ± 182 , 384 ± 121 , and 594 ± 61 CFU/m³, respectively. And that the airborne bacterial concentrations of SA was lowest among these six sampling sites, especially at 14:00 (105 ± 182 CFU/m³). In summer, the concentration of airborne bacteria of CK (1240 ± 151 CFU/m³), SN (594 ± 320 CFU/m³) and SA (769 ± 337 CFU/m³) at 14:00 were lower than other sampling times, which showed the total bacterial concentrations decreased as temperature increased, and there was significant reduction of the airborne bacterial concentrations of the forest community types of SN, SM, ST, and SA at 10 am ($p < 0.01$). In autumn, the concentration of airborne bacteria of SN (454 ± 160 CFU/m³) and ST (804 ± 242 CFU/m³) were lowest at 8 am, and CK (559 ± 242 CFU/m³), SM (349 ± 121 CFU/m³) and SK (349 ± 264 CFU/m³) were at 18:00, which means the airborne bacterial concentrations of the deciduous forests of SN and ST were higher than these in evergreen forests of SM and SK, especially significantly higher at 16:00 ($p < 0.05$).

Previous studies are in agreement with the result that reported seasonal and hourly variation in airborne bacterial concentrations (Hu et al. 2020). It was observed that airborne bacteria showed a distinct seasonal pattern with a significantly higher concentrations in the summer than other seasons. The shift of meteorological parameters over the four seasons may partially explain the seasonal variations in bacterial concentration (Leyronas and Nicot 2013). The weather of Chenzhou city is a subtropical monsoon climate with cold and less rain in winter, and hot and more rain in summer. In general, summer with high temperature and humidity (70–80%) is considered as a conducive season for microbial growth and reproduction (Genitsaris et al. 2017; Smets et al. 2016), which would lead to a higher bacterial concentrations in the air in summer. Due to the fact that the environment of the urban forest belongs to a special outdoor space, another possible reason for the high bacterial concentration of urban forest in summer and that low in winter, some plants bloomed in spring and summer (Jackson and Denney 2011; Redford and Fierer 2009), and withered or grew slowly in autumn and winter (Kozdrój et al. 2019). In addition, compared to the deciduous forests of SN and ST, the more leaves and the higher volatile organic chemicals concentrations (Aydin et al. 2014) were in evergreen forests of SM and SK, which may be the reason for the less airborne bacterial concentrations in autumn and winter. There is a possible explanation for these temporal-spatial disparities that the relative contributions of the site-specific biological sources at different times. Visitors, soil and vegetation may be the main sources of airborne bacteria at the urban forest park (Xie et al. 2018a). Hence, diverse environmental conditions and different environmental parameters around different sampling sites led to different seasonal concentration variations of airborne bacteria (Zhai et al. 2018).

Bacteriostasis of different forest communities

Large vegetated land covers such as forests emit substantial amounts of BVOCs, and approximately 1700 BVOCs emitted by 90 different plant families were defined in the literature (Knudsen and Gershenzon, 2006), which could lead to a harsher environment for airborne bacteria (Gao et al. 2005). In the present study, the bacteriostatic rates of the five forest community types were significant variable in each sampling sites in the same season, nevertheless, no significant effects varied in the broad-leaved forest community and green forest community over the four seasons (Fig. 4). In winter, the bacteriostatic rate of SA (mixed forest community) not only had significant differences with other sampling sites ($p < 0.05$), but also 14.3% higher than CK. In the spring, the concentration of airborne bacteria increased with tree sprouting and organisms revival, five sampling sites with the rate of SA (84.28%), SK (46.34%), ST (38.08%), SM (20.73%), and SN (14.63%) were lower than that in CK ($p < 0.05$), which indicate that there was significant variation of the bacteriostatic of coniferous forest and mixed forest. In summer, the bacteriostatic ability of forest was ordered as: SN (-51.01%) > SA (-43.76%) > SM (-35.48%) > ST (-13.69%) > SK (-8.72%) > CK with no significant difference ($p > 0.05$). The bacteriostatic rate of SN, SM, ST, SK and SA were - 6.67%, -53.85%, 30.77%, -24.1% and - 36.41% in autumn, respectively, with significant differences between SM and SA, and that the airborne bacterial concentration of ST was extremely higher than CK. As we know, BVOCs are able to decontaminate the air by inhibiting the growth and reproduction of airborne pathogens. It has been reported that BVOCs, such as limonene, α -pinene, β -pinene, and myrcene, inhibited the growth of bacteria, and that various conifer species emitted more BVOCs and a stronger bacteriostasis in terms of BVOCs (Aydin et al. 2014; Gao et al. 2005; Hong and Jin 2001). Whereas our results were not the same, the bacteriostasis and air-decontaminating effects of BVOCs were needed to further discuss in terms of their habitat factor. Thus, vegetative species had significant or extremely significant effects on airborne bacterial concentrations.

Factors influencing the bacterial concentration in different forest communities

Correlations between airborne bacterial concentration and influencing factors

During the whole sampling period, the environmental factors (meteorological elements, UV, NAI, PM and airborne bacteria) of air samples from the 6 sampling sites were observed (Table 2). Spearman's correlation coefficients of these parameters with the measured bacterial concentrations are presented in Fig. 5.

From the field data, Spearman's correlation analysis showed that forest community type was negatively correlated with the environmental factors except for RH and NAI, and there were significant correlations between forest community type and WS, T, UV, PM_{1.0}, PM₁₀, TSP, and airborne bacterial concentration ($p \leq 0.05$). Many related studies have reported that there were a positive correlation between forest and RH or NAI (Wang et al. 2020a; Wang et al. 2020b), and a negative correlation between forest and T, UV or airborne particulate matter (Wang et al. 2019). Whereas there were no significant correlations between forest community types and RH, NAI, or PM_{2.5} in this study ($p > 0.05$). In addition, meteorological conditions, such as T, RH, and WS, varied with the season, which led to significant correlations between temporal factors and environmental factors ($p \leq 0.05$). On the other hand, airborne bacterial concentration was found to be significantly positively correlated with WS, T, UV, NAI and TSP, especially for the season ($p \leq 0.05$), and significantly negatively correlated with PM_{2.5} and PM_{1.0} ($p \leq 0.05$). Several previous studies also have shown similar results, which indicated that there were correlations between airborne bacterial concentrations and environmental parameters (Frankel et al. 2012). What's more, seasonal variation has a significant impact on negative or positive correlations.

Spearman's correlation coefficients of environmental parameters with the measured airborne bacterial concentrations in every season are depicted in Table 3. There were seasonal differences between airborne bacterial concentration and the forest community type. Over the four seasons, the forest community type was found to be significantly negatively correlated with the airborne bacterial concentration in spring and summer ($p \leq 0.01$), and the correlation gradually tended to fade in autumn, and transformed positively in winter ($p \leq 0.01$).

Seasonal variations were found in the correlation between airborne bacterial concentration and environmental factors, and different environmental factors affecting airborne bacterial concentration were disparate in each season. In terms of season, the airborne bacterial concentration in the spring was susceptible to more environmental factors than others seasons. There were also seasonal differences existed in the correlation between airborne bacterial concentration and a single environmental factor. For example, the WS was found to be significant positively correlated with the airborne bacterial concentration in spring ($p \leq 0.05$) and autumn ($p \leq 0.05$), but no correlations in summer and winter. Genitsaris et al. (2017) found that no statistically significant correlation between WS and the concentration of the airborne bacteria. Meanwhile, a positive correlation was also detected between airborne bacterial concentration and RH in spring and summer (though not significant), and a negative correlation in autumn ($p \leq 0.01$) and winter, and the possible reasons were that the more frequent rain in spring and summer, whereas the less rain days in autumn and winter. The increase in air humidity would inhibit raising dusts and promote bacterial concentration (Almaguer et al. 2014). Furthermore, UV was as well as found to be positively correlated with airborne bacterial concentration in spring ($p \leq 0.01$), summer and autumn ($p \leq 0.05$), but negatively in winter. In forest, leaves of vegetation could block UV, which may have contributed to universally increase airborne bacterial survival, and leaves of some deciduous plants here fall in winter could lead to a significant negative influence on the culturability of airborne microorganisms by solar radiation intensity (Tang 2009). In addition, the correlation between airborne bacterial concentration and T was weak over the four seasons. While Genitsaris et al. (2017) reported that air temperature had a significant correlation with bacterial concentration. In this study, the average sample temperature (16.8 ± 4.8 °C) of the forest in winter was less than 24 °C, below which the cultivation of airborne bacteria is thought to universally decrease (Tang 2009).

Likewise, TSP was found to be positively correlated with airborne bacterial concentration in all seasons, particularly significant in the spring ($p \leq 0.01$) and summer ($p \leq 0.05$). The effects of PM_{2.5} and PM_{1.0} matter on airborne bacterial concentration were not remarkable, but the correlations between them were positive in spring and summer, and negative in autumn and winter. Guo et al. (2013) found that the airborne bacterial concentration had a significant positive correlation with TSP, but had a significant negative correlation with PM_{2.5} and PM_{1.0} in Beijing urban forest. Ren (Ren 2007) discovered that the airborne bacterial concentration had a significant positive correlation with TSP, but had a non-significant relationship with PM_{2.5} and PM_{1.0} in Beijing green space. These results are similar to our study. However, other studies in urban outdoor space of China, such as Jinan (Wei et al. 2020), Xi'an (Xie et al. 2018b), Beijing (Li et al. 2018), and Hangzhou (Liu et al. 2018), suggested that the bacterial concentrations were gradually increased as the particulate matter concentration

concentration went up from clean to moderately polluted, which are not consistent with our results. Maybe for the reason that the particle matters (PM_{2.5} and PM_{1.0}) were more easily affected by other factors such as forest microclimate and even had negative correlations with airborne bacteria. Besides, published research (Guo et al. 2013) on the biological effects of NAI revealed that NAI can inhibit the growth of bacteria, but the correlation between NAI and airborne bacterial concentration was weak in this study.

In summary, airborne bacterial concentration is controlled by multiple and variable abiotic and biotic factors, which among others may include the temporal variability, diverse vegetation types, forest micro meteorological, particulate matter concentrations, and human activities (Dong et al. 2018; Guo et al. 2013; Zhai et al. 2018), which not independent, rather, there are interactions.

Multiple linear regression of airborne bacterial concentration and environmental parameters

To further understand the effects of various parameters on airborne bacterial concentration, forest community type, T, WS, UV, NAI, TSP, PM_{2.5} and PM_{1.0} as independent variables, and airborne bacterial concentration as the dependent variable was used to establish a multiple linear regression model to analyse the cause of changes in airborne bacterial concentrations. The multiple linear regression model for airborne bacterial concentrations is shown as Equation (3).

$$\text{Bacterial concentration} = 1679.773 + 375.292\text{WS} + 1.651\text{UV} + 0.470\text{NAI} + 2.678\text{TSP} - 7.570\text{PM}_{2.5} \quad \text{Equation (3)}$$

Analytical results show that the R^2 was 0.178 ($p = 0.000$) for multiple linear regression modes, thus, the model reached a significant level and had statistical significance. According to Equation (3), the WS and UV have a significantly positive effect on the airborne bacterial concentrations ($p < 0.05$). Li et al. (2021) confirmed the importance of WS and UV for bacterial concentrations. Strong wind could bring in exogenous bacteria or dilute the concentration of local bacteria (Zhong et al. 2016). When the results among every season were compared, more sunshine, strong solar radiation and ultraviolet light were found in summer causing the airborne bacterial concentrations in summer to be higher than that in other seasons (Zhai et al. 2018). In addition, Equation (3) also shows that NAI and TSP significantly positively affect airborne bacterial concentrations ($p < 0.05$), and PM_{2.5} significantly negatively affects airborne bacterial concentrations ($p < 0.05$). This study found that with an increasing vegetation coverage, the lower bacterial concentration was. Since more vegetation coverage of evergreen broad-leaved forest and mixed forest and the TSP and PM_{2.5} concentrations are lower in the broad-leaved forest than coniferous forest, and evergreen forest than deciduous forest, there is a lower airborne bacterial concentration in SM and SA (Table 1 and Fig. 2). The result of this study is similar to the result of section 3.3.1 that meteorological parameters have a great effect on airborne bacterial concentrations, and the impact of meteorological factors on airborne bacterial concentration was greater than that of the airborne particulates, and Zhen et al. (2017) illustrated meteorological factors had more impact on airborne bacterial communities than air pollutants. However, forest community type, T and PM_{1.0} had no significant effect on airborne bacterial concentrations ($p \geq 0.05$). Gu et al. (2020) found that temperature played a key role in the concentration of airborne bacterial.

Conclusions

Field measurements of bacterial air quality in five forest communities were carried out in this study to identify the spatial and temporal variation distribution characteristics of airborne bacterial concentration, as well as to examine the influencing factors. The findings revealed that the bacterial concentrations of all the five communities of forest were the range of cleaner to clean levels. The airborne bacterial concentrations from least to highest appeared in the following order: SA (mixed forest), SM and SK (evergreen forests) > SN and ST (deciduous forests), SM and SN (broad-leaved forests) > ST and SK (needle-leaved trees). Highest bacterial concentrations in summer, and relatively low in winter, and the daily airborne bacterial concentrations of sampling forests showed an M-shaped trend. Spearman's correlation showed that significant correlations among forest community types, temporal factors and the environmental factors. In addition, the airborne bacterial concentrations in the spring were susceptible to more environmental factors than others' seasons. When a multiple linear regression model of airborne bacterial concentration in the forest, including the WS, UV, NAI, TSP and PM_{2.5} was established, the model showed statistical significance ($p = 0.000$). Our findings indicate that the mixed forest is the best selection for improving air quality and public healthcare, the regulation of urban forest communities could improve urban forest services by decreasing the efficiency of airborne bacterial concentration and airborne particulate matter.

Declarations

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Tables

Table 1 Outline of sampling sites

Sampling site	Forest community type	Plant species	Forest height m	Mean branch height m	DBH cm	Canopy density	Average age
CK	Blank	None	-	-	-	-	-
SN	Deciduous broad-leaved forest	Nyssa sinensis	13	5.0	27	0.7	45a
SM	Evergreen broad-leaved forest	Magnolia	15	3.0	28	0.8	45a
ST	Deciduous coniferous forest	Taxodium ascendens Brongn	15	3.7	26	0.6	45a
SK	Evergreen coniferous forest	Keteleeria pubescens	13	4.0	16	0.7	45a
SA	Mixed forest	Azalea and Pinus Massoniana	0.9-2.2	0.6	0.5-7	0.9	8a
			16	8.0	24	0.8	38a

Table 2 Environment parameters of the different forest communities in Nanling botanical garden

	CK			SM			ST			SK			SN			SA
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
W (m/s)	0.6 ±0.6	3.2	0.0	0.2 ± 0.2	0.8	0.0	0.2 ± 0.4	2.3	0.0	0.3 ± 0.3	1.2	0.0	0.3 ± 0.4	1.7	0.0	0.2 ± 0.3
T (°C)	27.3 ± 6.9	38.6	7.8	25.5 ± 6.5	35.9	7.9	24.9 ± 6.3	33.8	7.8	25.0 ± 6.1	33.8	8.2	25.3 ± 6.1	34.9	8.9	23. ± 6
H (%)	54 ± 15	86	31	58 ±14	87	35	59 ± 12	83	35	61 ±14	89	34	56 ± 12	97	32	59 17
UV (μW/cm²)	228 ± 273	949	0.00	18 ± 34	219	0	37 ± 43	303	0	9 ±11	47	0	73 ± 88	489	0	53 97
NAI (ions/cm³)	312 ± 239	818	0	695 ± 506	2133	0	805 ± 649	3093	0	778 ± 598	2288	0	586± 396	1788	0	53 679
PM1.0 (μg/m³)	9.09 ± 7.09	45.19	3.17	8.72 ± 6.46	33.77	3.13	7.12 ± 6.60	35.47	1.51	7.67 ± 8.46	39.03	1.48	8.48 ± 5.56	31.78	2.87	7.6 ± 8.2
PM2.5 (μg/m³)	29.54 ±40.88	334.52	6.90	28.13 ±20.05	93.20	12.09	23.99 ± 20.75	108.34	6.16	24.17 ± 23.27	111.78	5.74	28.19 ± 18.96	92.80	11.46	23. ± 21.
PM10 (μg/m³)	70.5 ± 26.7	165.7	19.3	59.3 ± 33.8	254.1	11.6	58.1 ± 24.1	117.0	13.8	55.7 ± 28.7	173.3	14.7	56.9 ± 26.2	114.9	14.2	45. ± 28.
TSP (μg/m³)	150.4 ± 81.6	381.7	25.8	114.8 ± 79.8	389.0	27.1	121.6 ± 68.1	319.0	7.3	105.3 ± 51.8	271.1	16.3	115.2 ± 65.7	276.5	16.9	86. ± 51.

Note: Number of collected air samples during the study period: 432 samples.

Table 3 Seasonal variation in the correlations between airborne bacterial concentration and environmental factors

	Spring	Summer	Autumn	Winter
FCT	-0.382a	-.391a	-0.092	0.242a
WS	0.326a	-0.030	0.247b	0.039
T	0.071	-0.075	0.146	-0.138
RH	0.076	0.043	-0.307a	-0.098
UV	0.449a	0.056	0.218b	-0.112
NAI	0.134	-0.060	-0.078	-0.247a
PM1.0	0.106	0.094	-0.157	-0.189b
PM2.5	0.029	0.207	-0.134	-0.202b
PM10	0.395a	0.200b	-0.035	0.041
TSP	0.417a	0.216b	0.036	0.048

Note: a indicates significance at the 0.01 level.

b indicates significance at the 0.05 level.

Figures

Figure 1

Location of the Nanling botanical garden

Figure 2

Box plot comparing airborne bacterial concentrations in the different sampling forest sites Note: The box frames represent the upper and lower quartiles, the line represents the median, the whiskers denote the range, and "□" represents the mean. "*" indicates a statistically significant difference between CK concentrations.

Figure 3

Concentration of airborne bacteria in different forests at temporal variation Note: Data are presented as mean $\pm$ SE ($n = 9$). "*" indicates a statistical significance ($p < 0.05$) among different forest community types (SN, SM, ST, SK, SA and CK) within the same sampling period.

Figure 4

Bacteriostatic rate of different forest community types in different seasons Note: Data are presented as mean $\pm$ SE (n = 54). Capital letters represent statistical significances ($p < 0.05$) between different forest community types (SN, SM, ST, SK, SA and CK) within the same season, and lowercase letters represent statistical significances ($p < 0.05$) between different seasons (spring , summer, autumn and winter) within one forest type.

Figure 5

Effects of the forest community type and temporal on forest environmental factors by Spearman's correlation analysis Note: Color intensity on the right represents the value of the correlation coefficient. The figure shows the correlation between forest spatio-temporal and environmental factors with a warm tone indicating positive correlation and cool indicating negative correlation. The darker the color, the bigger the circle, the greater the correlation. * means $p \leq 0.05$, significant mark.

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