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Screening of Tree Species for Improving Outdoor Human Thermal Comfort in a Taiwanese City

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Abstract: Tropical cities can use urban greening designs featuring trees that provide shade and cooling in hot outdoor environments. The cooling effect involves numerous tree characteristics that are not easy to control during planting design, such as the canopy size and the optical properties of leaves. Planting the appropriate tree species dominates the cooling effects and the human thermal environment. Based on environmental and plant data, including the tree species, crown diameter of trees, physiologically equivalent temperature (PET), and sky view factor (SVF) in an outdoor space, a series of hierarchical cluster analysis (HCA) procedures was implemented to identify the tree species that are appropriate for improving thermal comfort. The results indicated strong correlations between SVF, average crown diameter, and PET. SVF decreased as the average crown diameter increased. For the average crown diameter of trees in an area wider than 1.5 m, the cooling effect was especially dominated by the tree species. Therefore, 15 species were screened by HCA procedures, based on a similar cooling effect. These species had various cooling effects, and were divided into four categories. Tree species, such as *Spathodea campanulata* and *Cinnamomum camphora*, had the appropriate crown diameter and cooling effect for the most comfortable thermal environment.

Keywords: tree crown diameter; sky view factor (SVF); physiologically equivalent temperature (PET); thermal comfort; tree planting design; urban greening

1. Introduction

Because outdoor environments in tropical areas are hot, people who engage in outdoor daytime activities tend to prefer outdoor areas shaded by trees, to outdoor areas that are not shaded by trees [1]. A favorable tree planting design provides appropriate shade and cooling functions [2–5]. These functions not only influence microclimate modification, especially for tropical and subtropical regions [6–8], but also improve thermal comfort [9–11]. For example, the structures of tree crowns, and the shapes and colors of the leaves, influence the levels of visible light and solar infrared waves [6]. Small-leaved tree species tend to be more effective at cooling than larger-leaved species [12,13]. Therefore, the cooling effect and shading of plants is mainly determined by the canopy density, leaf arrangement, height, branch spread, bole height, solar radiation, and optical properties of the leaves [8,14,15].

Mature trees dominate the crown characteristics. Other tree characteristics, such as the leaf density, are either involved in complex processes or subject to considerable natural variability. The influence of different species on the outdoor thermal environment also differs by area [16]. A database of urban trees should be created to support landscape designers, and tree species should be evaluated for cities' tree planting plans and the maintenance of an urban microclimate that does not impair humans [6,17]. Several human-biometeorological variables, such as the standard effective temperature, predicted mean vote, mean radiation temperature (T_{mrt}), and physiological equivalent temperature

(PET), are used to evaluate human thermal comfort [18]. These variables for estimating outdoor thermal sensation are presented as functions of air temperature (T_a), wind speed, solar radiation intensity, and absolute humidity [19]. In European countries and Hong Kong, wind has a negative effect on thermal sensation, and high wind speed only becomes significant in thermal sensation in winter [19,20]. The sky view factor (SVF) describes the impact of canopy density on air circulation [8] and the irradiance reduction of plant canopies [9,10,21]. Because SVF can be measured conveniently, some studies have used SVF to discuss variations in shading levels and air temperature [22–25]. Areas with relatively dense broadleaf trees tend to have low SVF values [26]. High-SVF areas with thin broadleaf trees were shown to facilitate improved ventilation [27], but these areas also have low shading levels and are exposed to relatively high-air-temperature environments on summer days [28]. Therefore, SVF may be an integrated indicator to describe the crown characteristics. Hierarchical cluster analysis (HCA) is suitable for clustering targets with an unknown number of groups [29], and has been applied to identify pollution sources and assess rice production risks on the basis of the similarity of observations [30–32]. In addition, previous studies on the planting design of green spaces have investigated the visual effects, but not the functions, of plants.

The aim of this study was to improve outdoor human thermal environments through the appropriate choice of tree species for planting in open spaces, especially in the tropics. This study included a survey of environmental and planting parameters of outdoor spaces in Taiwan; parameters included the tree species, crown diameter, SVF, and meteorological and human-biometeorological variables. A database was created to support landscape designers. The relationships between these parameters were also discussed. Finally, HCA was used to choose appropriate tree species for tree planting in open spaces. This method could facilitate the improvement of thermal environmental comfort and climate adaptation in tropical urban areas.

2. Materials and Methods

2.1. Thermal Environment and Planting Design of Outdoor Space

Our study was conducted in the outdoor space of Chiayi Park (23.48°N, 120.47°E), which is located in southern Taiwan, and experiences subtropical and tropical climates (Figure 1). July is the hottest month, with a maximum air temperature of 33.1 °C and an average air temperature of 25.2 °C. The monthly average relative humidity (RH, %) is 75%–85% and the average vapor pressure during 2011–2015 was 27 hPa–32 hPa, indicating that this outdoor space experiences hot summers and high year-round humidity. Chiayi Park features a rich ecology and abundant relaxation facilities. Additionally, various shaded spaces provide park visitors with space for outdoor activities. In Figure 1, a total of 12 sites, including A1, A2, A3, B1, B2, B3, C1, C2, C3, D1, D2, and D3, can be seen, that could encourage more people to participate in activities and which have a low wind speed. A wind meter (R M Young 81000) was used to record the wind speed at a height of 1.1 m above the ground, and the average wind speed for each measurement was <0.5 m/s. For evaluating outdoor human thermal environments and reducing the interference of wind, the 12 sites were chosen as measurement sites. Environmental and planting parameters, such as plant characteristics, SVF, and meteorological and human-biometeorological variables, were measured at the 12 sites (Figure 1). Measurements were taken during the summer (July–October 2014) because this season witnesses the maximum use of shaded spaces.

Meteorological and human-biometeorological variables, including T_a, T_{mrt}, globe temperature (T_g), and PET, were measured to evaluate the outdoor thermal comfort [33]. RH, T_a, and T_g were sampled at a height of 1.1 m above the ground. A black globe thermometer was used to record T_g, and a Center 314 humidity and temperature meter was used to record the humidity and T_a. Measurements were recorded automatically and simultaneously at 1-min intervals, from 10:00 to 16:00, as the T_a of this period is hot; the temporal resolution of 2 h of recorded data will be adopted for further analysis. The recorded meteorological data per day was selected, according to similar weather conditions;

for example, the recorded data was not selected for analysis when it rained during the day. T_{mrt} was calculated using T_a, T_g, and wind velocity, on the basis of ISO standard 7726 [34,35]. To obtain the values of PET [36,37], parameters including T_a, relative humidity, wind speed, and T_{mrt}, were entered into RayMan software package [38].

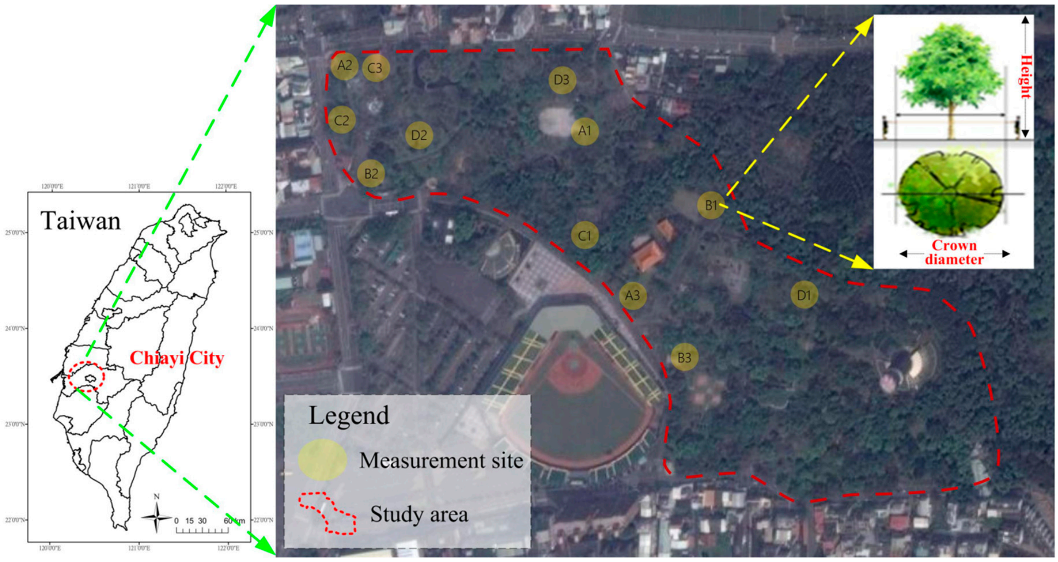


Figure 1. Measurement sites of environmental parameters in the study area.

The studied area included 95 types of plant. Plant characteristics, such as tree species, tree height (m), crown diameter (m), and diameter at breast height (m), were recorded. Tree height, measured from the base to the tip of the tree, was measured using a Christen hypsometer [39]. The crown diameter of each tree was obtained by taking the arithmetic mean of the horizontal crown diameter measured on the north-south axis, and again on the east-west axis [40]. The diameter at breast height was obtained by directly measuring the diameter of the trunk with a tape. GPS was used to locate the plant which had been measured, and photographs of the plant were recorded. Photographs or leaves were collected and compared with the literature to confirm the tree species [41], and the data were entered into a geographic information system database. In addition, SVF was determined using a fish-eye lens at a height of 1.1 m above the ground and RayMan software package [6,38].

2.2. Screening of Appropriate Tree Species Using HCA

HCA is a popular method for discovering patterns in large observed data and clusters targets according to the similarity of observations (or variable) [42]. Groups of tree species with similar characteristics were identified using HCA. The distance between two tree species was defined as the Euclidean norm of the difference between the centered and scaled vectors of their characteristics. The dissimilarity between clusters, based on this distance, was defined using Ward's method; the standardized *m*-space Euclidian distance is given by the following equation [43]:

$$d_{ij} = \sqrt{\frac{\sum_{k=1}^{m}\left(X_{ik} - X_{jk}\right)^2}{m}}$$

where X_{ik} denotes the *k*th measured variable for observation *i* and X_{jk} is the *k*th measured variable for observation *j*. In the HCA dendrogram, a short distance indicates that the two observations are similar or "close together", and vice versa. Detailed calculation processes of HCA can be found in a classical paper conducted by Punj and Stewart (1983) [44]. Some common decision rules, such as the R-squared (R^2) and semipartial R-squared (SPR) rules, were recommended for screening the appropriate observations and evaluating the numbers of groups; the number of groups should be chosen such that a further reduction results in a substantial decrease in the SPR [45]. Within the analysis, when the rule values were bad, the inappropriate observations were removed, and the HCA was implemented progressively, until better rule values were obtained. In this study, the data were analyzed using SPSS 18 software.

Specifically, tree species were classified into the same group if they had a similar cooling effect; the variables, including crown diameter, SVF, and PET, were the inputs of HCA. The process was repeated to identify the appropriate tree species and determine the number of groups, according to the R^2 and SPR rules. However, because trees with low heights did not cause shading and cooling effects, when they were located near other trees with higher heights, the HCA procedures for screening the appropriate tree species were conducted on the basis of the survey data for the trees near the SVF measurement sites that were higher than 2 m. In addition, the discovered patterns depended on the observations, climatic conditions, and geological environment.

3. Results and Discussion

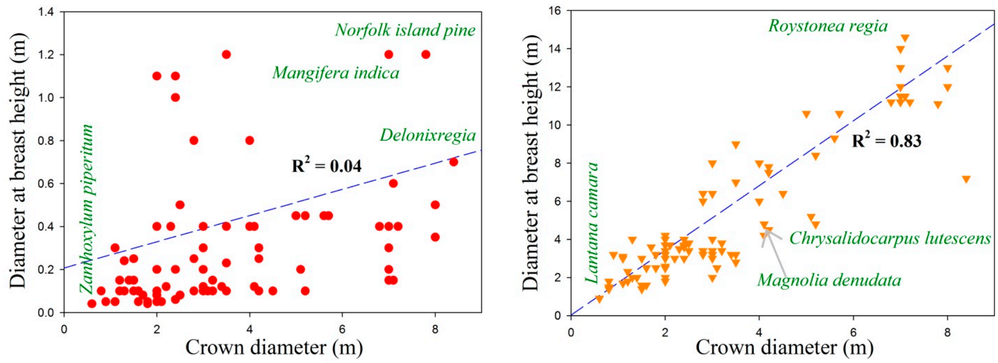
3.1. Tree Database and the Relationships between Average Crown Diameter, Plant Height, Diameter at Breast Height, and SVF

The tree database comprised 614 trees that were surveyed in the study area, and Table 1 shows the classification of tree species according to the average crown diameter. Ten plant species were identified with crown diameters exceeding 10 m; twenty-five plants species were identified with crown diameters between 5 and 10 m; and twenty-one plants species were identified with crown diameters between 3 and 5 m.

Table 1. Plant species in the database.

Average Crown Diameter	Plant Specie
Crown diameters exceeding 10 m	*Tectona grandis*, *Peltophorum pterocarpum*, *Cerbera manghas*, *Hibiscus tiliaceus*, *Ficus microcarpa*, *Betula pendula*, *Delonix regia*, *Haematoxylum campechianum*, *Zelkova serrata*, and *Terminalia catappa*
Crown diameters between 5 and 10 m	*Roystonea regia*, *Lagerstroemia speciosa*, *Terminalia catappa*, *Araucaria heterophylla*, *Terminalia mantaly*, *Adenanthera pavonina*, *Pongamia pinnata*, *Spathodea campanulata*, *Melaleuca leucadendra*, *Magnolia denudate*, *Pterocarpus indicus*, *Phoebe faberi*, *Michelia figo*, *Mangifera indica*, *Araucaria cunninghamii*, *Tabebuia impetiginosa*, *Machilus zuihoensis* Hayata, *Saraca asoca*, *Alstonia scholaris*, *Liquidambar formosana* Hance, *Acer*, *Cinnamomum camphora*, *Mangifera indica*, *Bauhinia blakeana*, and *Terminalia catappa*
Crown diameters between 3 and 5 m	*Macaranga tanarius*, *Pithecellobium dulce*, *Cassia fistula*, *Chamaecyparis obtusa*, *Chorisia speciosa*, *Bischofia javanica* Blume, *Melia azedarach*, *Swietenia mahagoni*, *Calocedrus formosana*, *Hyophorbe verschaffeltii*, *Sterculia foetida*, *Pistacia chinensis*, *Elaeocarpus sylvestris*, *Pinus jeffreyi*, *Cocos nucifera*, *Syzygium samarangense*, *Juniperus chinensis*, *Dimocarpus longan*, *Barringtonia racemosa*, *Artocarpus altilis*, and *Codiaeum variegatum*
Crown diameters smaller than 3 m	*Lagerstroemia subcostata*, *Gordonia axillaris*, *Caryota urens*, *Carica papaya*, *Calocedrus formosana*, *Fraxinus griffithii*, *Hibiscus rosa-sinensis*, *Podocarpus nagi*, *Washingtonia robusta*, *Bambusa vulgaris* Schrad, *Duranta erecta*, *Salix babylonica*, *Ficus benjamina*, *Zanthoxylum piperitum*, *Cananga odorata*, *Strelitzia nicolai*, *Michelia compressa*, *Triadica sebifera*, *Hyophorbe lagenicaulis*, *Pachira aquatica*, *Lantana camara*, *Prunus mume*, *Sapindus*, *Lagerstroemia speciosa*, *Ficus religiosa*, *Aucuba japonica*, *Erythrina variegate*, *Chrysalidocarpus lutescens*, *Allamanda schottii*, *Broussonetia papyrifera*, *Garcinia subelliptica* Merr., *Plumeria alba*, *Aglaia odorata*, *Elaeocarpus serratus* Linn., *Agave americana*, *Phoenix roebelenii*, and *Euphorbia splendens*

Figure 2 shows the relationships between the crown diameters, diameters at breast height, and the plant heights of the trees. In Figure 2a, the trees with the longest diameters at breast height are the Norfolk Island pine and *Mangifera indica*; the tree with the shortest diameter at breast height was *Zanthoxylum piperitum*. The tree with the widest crown diameter was *Delonix regia*, and the tree with the narrowest crown diameter was *Lantana camara*. As expected, the low regression coefficient (R^2 = 0.04) demonstrated no correlation between the tree diameter at breast height and the crown diameter. As shown in Figure 2b, the highest and lowest tree species were *Roystonea regia* and *Lantana camara*, respectively. Some trees with similar heights had different crown diameters, possibly because they were different tree species and had different soil environments. For example, specimens of *Magnolia denudata* and *Chrysalidocarpus lutescens* were both 4.8 m high, but they had crown diameters of 4.1 and 5.2 m, respectively. However, the high regression coefficient (R^2 = 0.83) indicated a high correlation between the tree height and the crown diameter; the crown diameter increased with increasing tree height in the study area.



(**a**) (**b**)

Figure 2. Relationship between (**a**) crown diameter and diameter at breast height (**b**) crown diameter and plant height.

Table 2 shows the actual sky view situation (fish-eye lens), SVFs at 12 measuring sites (Figure 1), and the tree species near the SVF measurement sites. A total of 56 tree species were located within 15 m of the SVF measurement centers, and SVFs varied from 0.025 to 0.637. A low SVF value indicated a lower visible sky value and a high leaf density value; the highest and lowest SVF values were measured at sites A2 and D3, respectively. Because sites with low SVF values had high shaded area values, people tended to do activities there during hot conditions [1,28]. Figure 3 reveals the relationship between SVF and the average crown diameter of trees at the 12 measurement sites. The average crown diameters varied from 0.6 to 8.4 m. The high R^2 indicated a significant correlation between SVF and the average crown diameter, and SVF decreased with increasing crown diameter in the study area. An inversion point was also observed. This revealed that SVF increased and the shaded area substantially decreased, when the average crown diameter of trees was less than 1.5 m.

Table 2. Plant species, sky view, and SVF values near the measurement sites.

Site [a]	Fish-Eye Lens	SVF	Plant Species *
A1		0.611	*Ficus religiosa*, *Adenanthera pavonina*, *Roystonea regia*, *Pterocarpus indicus*, *Cinnamomum camphora*, *Artocarpus altilis*, *Juniperus chinensis*, *Liquidambar formosana* Hance, and *Lagerstroemia speciose*
A2		0.637	*Chorisia speciosa*, *Hibiscus tiliaceus*, *Allamanda schottii*, *Peltophorum pterocarpum*, and *Ficusmicrocarpa*

Table 2. *Cont.*

Site [a]	Fish-Eye Lens	SVF	Plant Species *
A3		0.544	*Cinnamomum camphora*, *Chamaecyparis obtusa*, *Juniperus chinensis*, *Lagerstroemia speciosa*, and *Swietenia mahagoni*
B1		0.419	*Bauhinia blakeana*, *Tabebuia impetiginosa*, *Alstonia scholaris*, *Delonix regia*, *Ficus microcarpa*, *Spathodea campanulata*, and *Terminalia catappa*
B2		0.420	*Garcinia subelliptica* Merr., *Ficus benjamina*, *Peltophorum pterocarpum*, *Liquidambar formosana* Hance, *Juniperus chinensis*, *Euphorbia splendens*, *Magnolia denudata*, *Ficus microcarpa*, and *Lagerstroemia speciose*
B3		0.411	*Pterocarpus indicus*, *Ficus microcarpa*, *Delonixregia*, *Calocedrus formosana*, *Roystonea regia*, *Fraxinus griffithii*, *Chorisia speciosa*, *Cinnamomum camphora*, *Spathodea campanulata*, *Adenanthera pavonina*, *Pterocarpus indicus*, *Magnolia denudata*, and *Cassia fistula*
C1		0.047	*Lagerstroemia speciosa*, *Cinnamomum camphora*, *Michelia figo*, *Acer*, *Alstonia scholaris*, *Cinnamomum camphora*, *Chamaecyparis obtusa*, *Juniperus chinensis*, *Spathodea campanulata*, *Adenanthera pavonina*, and *Pterocarpus indicus*
C2		0.075	*Lagerstroemia speciosa*, *Peltophorum pterocarpum*, *Acer*, *Delonix regia*, *Alstonia scholaris*, *Haematoxylum campechianum*, *Bauhinia blakeana*, and *Roystonea regia*
C3		0.065	*Pachira macrocarpa*, *Elaeocarpus serratus* Linn., *Terminalia catappa*, *Ficus religiosa*, *Lagerstroemia subcostata*, *Araucaria cunninghamii*, *Pithecellobium dulce*, *Chrysalidocarpus lutescens*, *Roystonea regia*, *Peltophorum pterocarpum*, *Caryota urens*, *Chrysalidocarpus lutescens*, *Liquidambar formosana* Hance, *Sapindus*, *Ficus microcarpa*, *Peltophorum pterocarpum*, and *Lagerstroemia speciose*

Table 2. *Cont.*

Site [a]	Fish-Eye Lens	SVF	Plant Species *
D1		0.025	*Tectona grandis*, *Delonix regia*, *Alstonia scholaris*, *Bischofia javanica* Blume, *Swietenia mahagoni*, *Pistacia chinensis*, *Elaeocarpus serratus* Linn., and *Terminalia catappa*
D2		0.059	*Chrysalidocarpus lutescens*, *Peltophorum pterocarpum*, *Ficus microcarpa*, *Michelia compressa*, *Mangifera indica*, *Pongamia pinnata*, *Araucaria heterophylla*, *Swietenia mahagoni*, and *Liquidambar formosana* Hance
D3		0.138	*Cassia fistula*, *Pithecellobium dulce*, *Pongamia pinnata*, and *Pistacia chinensis*

[a] The site shown in Figure 1; * the trees height were higher than 2 m.

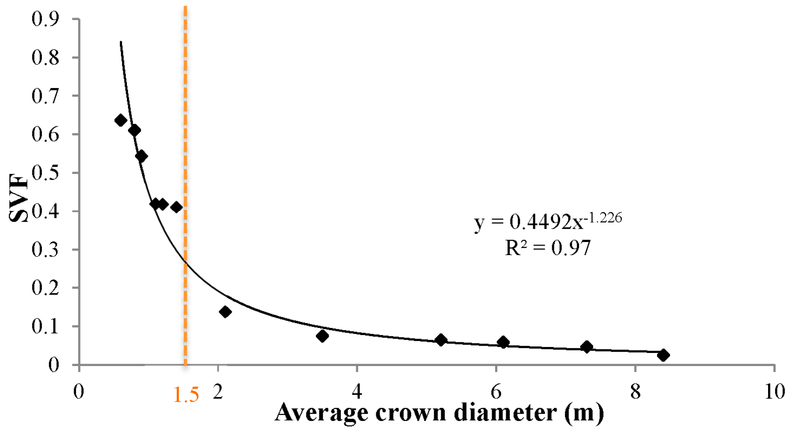


Figure 3. Relationship between SVF and average crown diameter of trees around the measurement site.

3.2. Relationship between Crown Diameters of Plants, PET, and T_{mrt}

Figure 4 shows the relationship between the crown diameters of plants, PET, and T_{mrt} at the measurement sites; PET was strongly correlated with T_{mrt}. When the average crown diameter was shorter than approximately 1.5 m, PET was usually higher than 40 °C and SVF was larger than 0.411; thus, the corresponding outdoor thermal comfort feeling ranged from hot to very hot [46]. Comparatively, the trees with average crown diameters wider than 1.5 m, introduced cooling effects and resulted in a lower PET; however, the cooling level was not correlated with the average crown diameter when PET was between 20 °C and 40 °C. These results indicate that the tree species with average crown diameters narrower than 1.5 m result in a larger open sky, causing a hot thermal environment. When the average crown diameter of trees was wider than 1.5 m, the cooling effect was affected by other tree characteristics, in addition to the crown diameter, such as the optical properties of leaves. However, tree characteristics were not easy to control, in order to improve outdoor thermal comfort. Therefore, screening of the appropriate tree species is essential for improving outdoor thermal comfort.

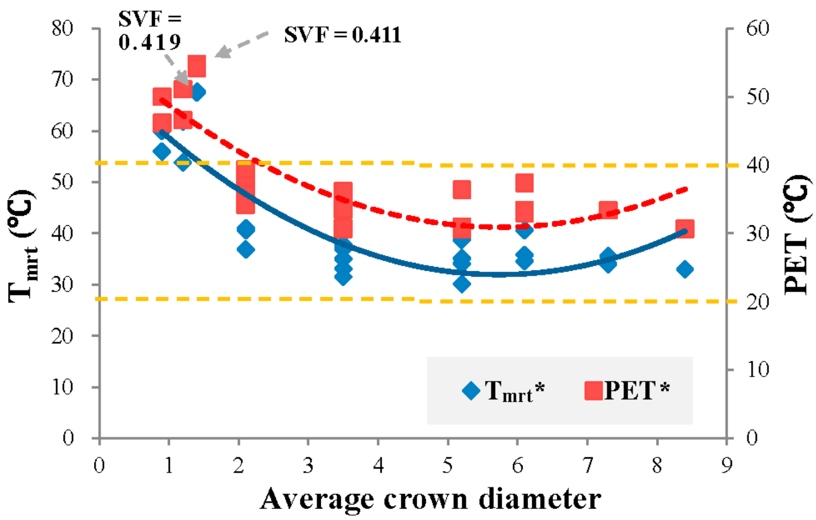


Figure 4. Relationship between average crown diameter of plants, PET, and T_{mrt}. * The value is average of 2 h of recorded data.

3.3. Appropriate Tree Species for Improving Outdoor Thermal Comfort

After implementing a series of HCA procedures on the screening of appropriate tree species, the results suggested that 14 species had similar cooling effects (Figure 5). In addition, significant reductions in the SPR and the R^2 from four groups to three groups, indicated that the four-group solution was the most appropriate, and the tree species for the four groups are shown in Table 3. *Ficus microcarpa* was the only tree species in Group A; the trees in Group B included *Delonix regia* and *Terminalia catappa*; the trees in Group C were *Juniperus chinensis*, *Bischofia javanica* Blume, and *Chamaecyparis taiwanensis*; and the trees in Group D included *Michelia figo*, *Acer*, *Spathodea campanulata*, *Cinnamomum camphora*, *Liquidambar formosana*, *Araucaria cunninghamii*, and *Pistacia chinensis*. The corresponding environmental conditions in which these 15 species exist, are shown in Figure 6; the thermal environment of the study area can be categorized as one of three sections, on the basis of the Taiwanese PET classification [46]: "Cool", "Comfortable", and "Warm to Hot". The tree species in Groups A and B had wider crown diameters than those in the other groups, and they had superior cooling effects. Tree species in Group C had narrower crown diameters and an inferior cooling effect. The tree species in Group D had wider crown diameters than those in Group C, and a cooling effect that created the most comfortable thermal environment in the study area. The cooling characteristics of the species in Group D could provide designers with planting design references for thermal environments. In addition, the HCA procedure used in this study could serve as a useful tool for identifying appropriate species.

Table 3. Plant species in different groups.

Group *	Plant Species
A	*Ficus microcarpa.*
B	*Delonix regia*, and *Terminalia catappa*
C	*Juniperus chinensis*, *Bischofia javanica* Blume, and *Chamaecyparis taiwanensis*
D	*Michelia figo*, *Acer*, *Spathodea campanulata*, *Cinnamomum camphora*, *Liquidambar formosana*, *Araucaria cunninghamii*, and *Pistacia chinensis*

* Group screened by a series of HCA procedures.

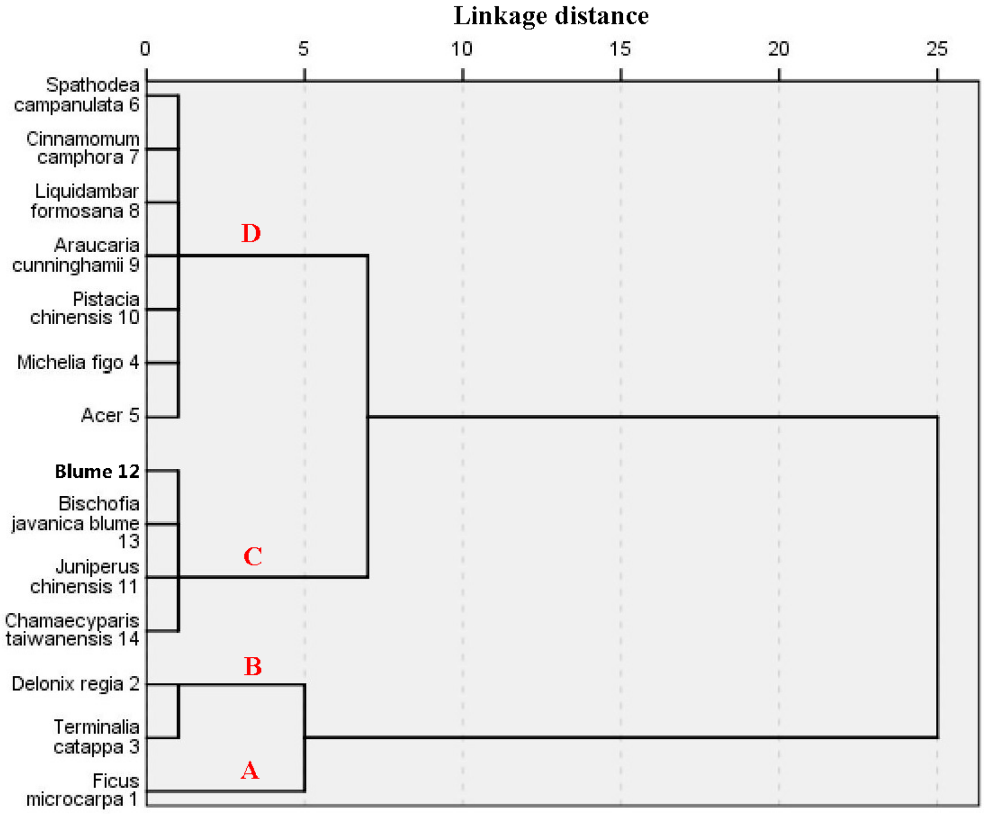


Figure 5. Cluster dendrogram grouping tree species with similar cooling patterns.

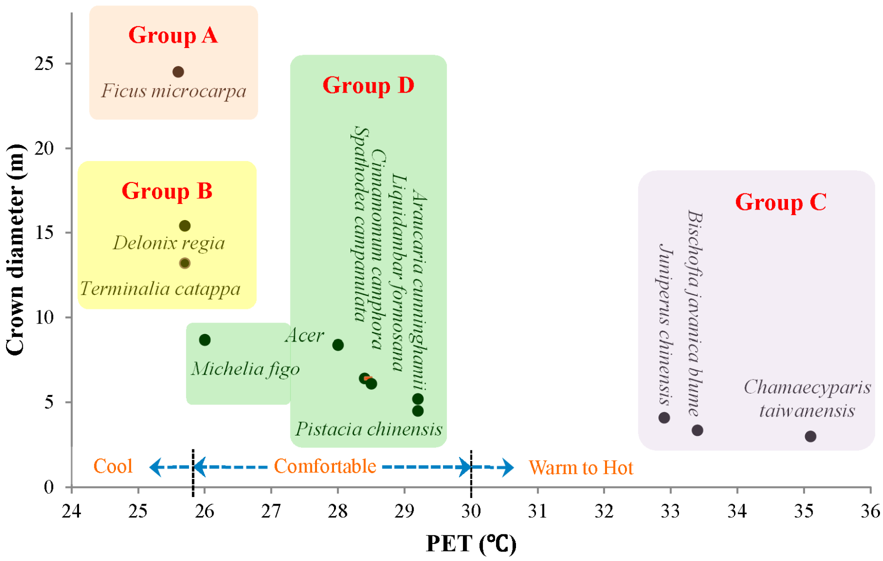


Figure 6. Thermal comfort range of outdoor landscape plants.

4. Conclusions

Taiwan experiences subtropical and tropical climates, and the thermal environments of outdoor spaces in urban areas are hot, especially at noon and during the afternoon. Improved planting design provides trees with shade and cooling functions that improve the thermal comfort of the outdoor space. The cooling effects involve complicated tree characteristics such as canopy size, tree height, and the optical properties of leaves. However, such tree characteristics are not easy to control, in order to improve outdoor thermal comfort. Therefore, planting the appropriate tree species dominates the cooling functions. In addition, the improvements made by different species to outdoor thermal environments varied greatly in different areas. Therefore, adopting a method to determine the appropriate tree species for planting design reference is essential. This study investigated environmental and plant data, including the tree species, crown diameter, meteorological and human-biometeorological variables, and SVF, in an outdoor space in Taiwan. A series of HCA procedures were applied to identify the appropriate trees species which could improve the thermal comfort of the outdoor space.

The results indicated a significant correlation between SVF and the average crown diameter, and they demonstrated that the SVF value decreased with the increasing average crown diameter of trees in the study area. When the average crown diameter was less than 1.5 m, the SVF value increased dramatically, and the shaded area substantially decreased. The trees with average crown diameters narrower than 1.5 m tended to have high SVF and a low canopy, and then the low irradiance reduction of the plant canopy would result in a high land surface temperature and hot environment. When the average crown diameter of the trees was wider than 1.5 m, the cooling effect was dominated by the other tree characteristics. This result indicated that planting appropriate tree species is the way to effectively improve outdoor thermal comfort in tropical climate areas. Fifteen species were identified by the HCA procedures with different cooling effects, and they were divided into four categories. The plants *Ficus microcarpa, Delonix regia, and Terminalia catappa*, had the most effective cooling effects. By contrast, *Juniperus chinensis*, *Bischofia javanica* Blume, and *Chamaecyparis taiwanensis,* had the least effective cooling effects. Other tree species had relatively large crown diameters and appropriate characteristics for cooling effects. Therefore, the HCA procedures are a useful tool for identifying the right tree species and improving the thermal comfort of open spaces. These results can serve as a reference for outdoor landscape planting designers in urban areas of the tropics. Planting the right trees in cities can also adapt those cities to climate change.

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Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Yu-Hao Lin and Kang-Ting Tsai conceived and designed the experiments; Kang-Ting Tsai performed the experiments; Yu-Hao Lin and Kang-Ting Tsai analyzed the data; Yu-Hao Lin and Kang-Ting Tsai contributed reagents/materials/analysis tools; Yu-Hao Lin and Kang-Ting Tsai wrote the paper". Authorship must be limited to those who have contributed substantially to the work reported.

Conflicts of Interest: The authors declare no conflict of interest.

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