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A Study on Street Tree Planting Strategy in Pingtan Island Based on Road Wind Environment Simulation

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Abstract: In this paper, the landscape of typical roadway trees and their planting parameters on Pingtan Island are investigated and analyzed in the field. A three-dimensional model of street trees was created using AutoCAD 2020, and Ansys Fluent 2022 was used to simulate the wind condition of trees with various planting parameters under high wind circumstances. The study explores the stress and adaptability of roadway trees in the wind environment under different planting parameters, such as different heights, plant spacing, lower shrub heights, and two-row and three-row planting with different row spacings. The results show that the wind resistance of street trees is connected to the planting parameters and that modifying the appropriate planting parameters can improve the wind stability of road green space. The height of street trees is more suitable between 6.0~9.0 m. The planting spacing should be not less than 1.0 times the crown and not more than 1.75 times the crown. The form of planting has an important effect on wind resistance. Two rows of planting of street trees have a better utility and wind resistance, and a row spacing of 2.0~6.0 m is more appropriate. The height of the lower shrubs should be lower than the height of the first branch, with 0.5~1.0 m being more suitable. Based on the results of the data simulation and analysis, this paper proposes corresponding tree species selections and planting strategies for road green belts on Pingtan Island from the perspective of street tree species, planting parameters, and planting forms to provide references for the upgrading and planning of roadway tree landscapes on Pingtan Island as well as in similar climatic regions.

Keywords: Ansys Fluent; planting parameters; road greenbelt; wind resistance

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1. Introduction

The dispersion of particulate pollution, outdoor thermal comfort, and the energy efficiency of urban buildings are all significantly impacted by the wind environment, which is an essential component of the urban habitat [1]. The overall wind environment is growing more complex due to the acceleration of urbanization and the density of urban buildings, and the local urban wind environment is degrading due to the interaction of wind direction and speed [2]. Urban building density and wind field strengths produce "wind tunnel effects" that directly affect people's day-to-day lives [3].

Road green space is the primary location for people to engage in outdoor activities, typically making up more than 25% of the metropolitan area [4], and it is crucial in enhancing the stability of the urban wind environment [5]. One way to improve the urban wind environment is through tree planting, which has several benefits, including high ecological resilience, a good landscape effect, and mobility [6,7]. Many scholars have discovered a mutual influence role of trees and wind environment through wind tunnel experiments [8], computational fluid dynamics [9], numerical simulation [10], and other research methods. The average wind speed of streets planted with street trees is lower than that of streets without tree planting, demonstrating that street trees have a significant impact on the wind environment of the roadway green space. Consequently, considering the wind environment when designing an urban street tree planting scheme is crucial.

The most widely used research methodology for simulating urban wind conditions is computational fluid dynamics (CFD) [11,12]. One of the most widely used CFD systems, Ansys Fluent 2022 software, is distinguished by its high operability, broad pre- and post-processing toolkit, and fine mesh production [13]. Through simulation research, numerous academics have discovered that street tree planting can alter local airflow patterns [14], which has a big impact on how the road wind environment is built [15]. Tree wind resistance and the street wind environment are improved in different ways depending on the height and crown width of street trees [9], as well as on the planting patterns [16–18].

The previous studies were all simulated studies on the stresses of single trees or single rows of trees in high winds (Table 1), and research is scarce on the stresses of trees interfering with one another between rows. Additionally, multi-row planting is a successful windproof planting technique when it comes to windy urban street trees or green barrier planting. Therefore, this article includes a simulation of two-row and three-row tree planting forms under high wind conditions. The impacts of common street tree planting methods on tree wind resistance and road wind environment are explored. Suggestions and references are provided for designing road planting landscapes on Pingtan Island and other wind-prone areas.

Table 1. Summary of previous research.

Simulation Tools	Researchers	Research	The Year of Research
Wind Tunnel Experiment	He et al. [11]	Wind tunnel test on wind-induced responses of roadside trees	2019
Wind Tunnel Experiment	Li et al. [19]	Wind Tunnel Test on Wind Load and Flow Field Characteristics of Trees	2020
CFD	Hosseinzadeh A et al. [17]	Computational Simulation of Wind Microclimate in Complex Urban Models and Mitigation Using Trees	2021
CFD	Amani-Beni M et al. [9]	Investigating the effects of wind loading on three-dimensional tree models using numerical simulation with implications for urban design	2023
Ansys Fluent	Buccolieri R et al. [14]	Analysis of local-scale tree–atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction	2011
Ansys Fluent	Amorim JH et al. [15]	Detailed modelling of the wind comfort in a city avenue at the pedestrian level	2012
Ansys Fluent	Wei et al. [13]	An empirical study of two numerical models for wind resource simulation in complex terrain	2014
Ansys Fluent	Zeng et al. [20]	Influence of Urban Road Green Belts on Pedestrian-Level Wind in Height-Asymmetric Street Canyons	2022
Ansys APDL	Zhang et al. [7]	Finite element modeling of wind resistance of single trees based on the linear filtering method	2016
MACROSCOPIC	Chen et al. [12]	The impacts of building height variations and building packing densities on flow adjustment and city breathability in idealized urban models	2017

Table 1. *Cont.*

Simulation Tools	Researchers	Research	The Year of Research
PHOENICS	Li et al. [17]	The Effect of Tree-Planting Patterns on the Microclimate within a Courtyard	2019
OpenFOAM	Wang et al. [10]	Numerical study on flow field and pollutant dispersion in an ideal street canyon within a real tree model at different wind velocities	2021

Pingtan Island is located in the Pingtan Comprehensive Experimental Zone of Fujian Province, on the southeast end of the Asian continent, east of the North Pacific and the East China Sea, and has a subtropical marine monsoon climate. Pingtan Island experiences high wind frequency and intensity due to climatic circumstances, with an average of 84.5 days of high wind (above grade 8) every year [20] (Figure 1), making it one of Fujian Province's strong wind locations. As a result, urban greening on Pingtan Island is hampered by issues such as the low wind resistance of street trees, tilted tree crowns, and significant safety threats from tree-shaped structures, and the stability of the road wind environment is jeopardized [21] (Figure 2). More studies have been done in the past on the selection of wind-resistant tree species for island-style towns, and several tree species that are good for planting in windy coastal locations have been screened out. However, what sort of planting form can maximize the benefits of wind resistance for these trees? To improve the ecosystem of island towns and provide a safe and comfortable living space, it is crucial to conduct research on roadway tree planting strategies based on roadway wind environment simulation.

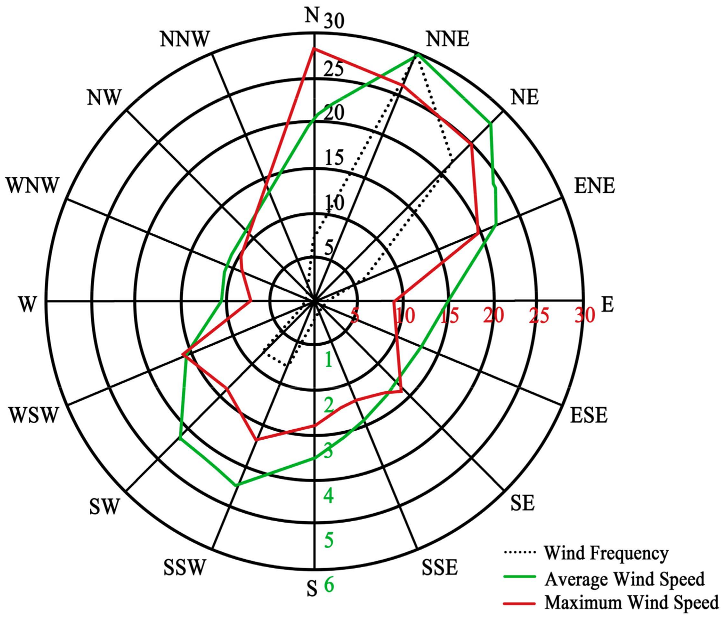


Figure 1. The wind rose map of Pingtan Island from 1971 to 2010. (Dashed line is the wind frequency; Green line is the average wind speed; Red line is the maximum wind speed).

This study aims to investigate the procedures and regulations for improving the roadside green space's wind environment through vegetation design. It is based on the actual data measurements of the street trees at the site and uses the research method combining field measurements and Ansys Fluent software simulation [19]. It analyzes the specific impacts of tree planting parameters and planting forms on the road wind environment for the particular wind environment formed in the road green space. The purpose is to offer a point of reference for the development and enhancement of the tree landscape along the roads in Pingtan Island and other climate-similar locations.

Figure 2. Status of street trees on Pingtan Island. (**a**) Tilted tree crowns. (**b**) Tree structures are a major safety hazard. (**c**,**d**) Poor wind resistance of trees. (Photos are by the author).

2. Methods

2.1. Overview of the Study Area

Pingtan Island is located in Fujian Province's Pingtan Comprehensive Experimental Zone, on the southeastern end of the Asian continent, facing the North Pacific Ocean and the East China Sea to the east. The monsoon and ocean currents affect Pingtan Island's subtropical oceanic monsoon climate, which is characterized by longer and deeper cyclone activity in the fall and winter, particularly during the winter when wind force is the strongest [20]. The number of days with severe winds (above grade 8) is 84.5 per year, making it one of the strongest wind regions in Fujian Province. Studying how street trees affect the wind environment of roads in windy seasons like fall and winter is, therefore, more applicable.

This study focuses on the effects of arborvitae street trees on the highway wind environment because it has been demonstrated that trees have a stronger impact on the wind environment at pedestrian heights than shrub plants and groundcovers [22]. The primary and secondary arterial roads on Pingtan Island served as the study's research object. The roads that were chosen for the study had to meet certain requirements, like having a significant number of listed street trees and a wide variety of road trees, a high volume of traffic, and street trees that had been growing steadily for more than two years, measuring more than 150 cm at the base of the first branch and more than 8 cm at breast height, and growing in good condition, all of which were necessary to ensure that the variables were all equal. The selection of eight six-lane and four-lane highways in the east-west, north-south, northeast-southwest, and northwest-southeast directions was based on the types of roads found on Pingtan Island and their distribution status throughout the island. Sample road distributions and vegetations are depicted in Figures 3 and 4.

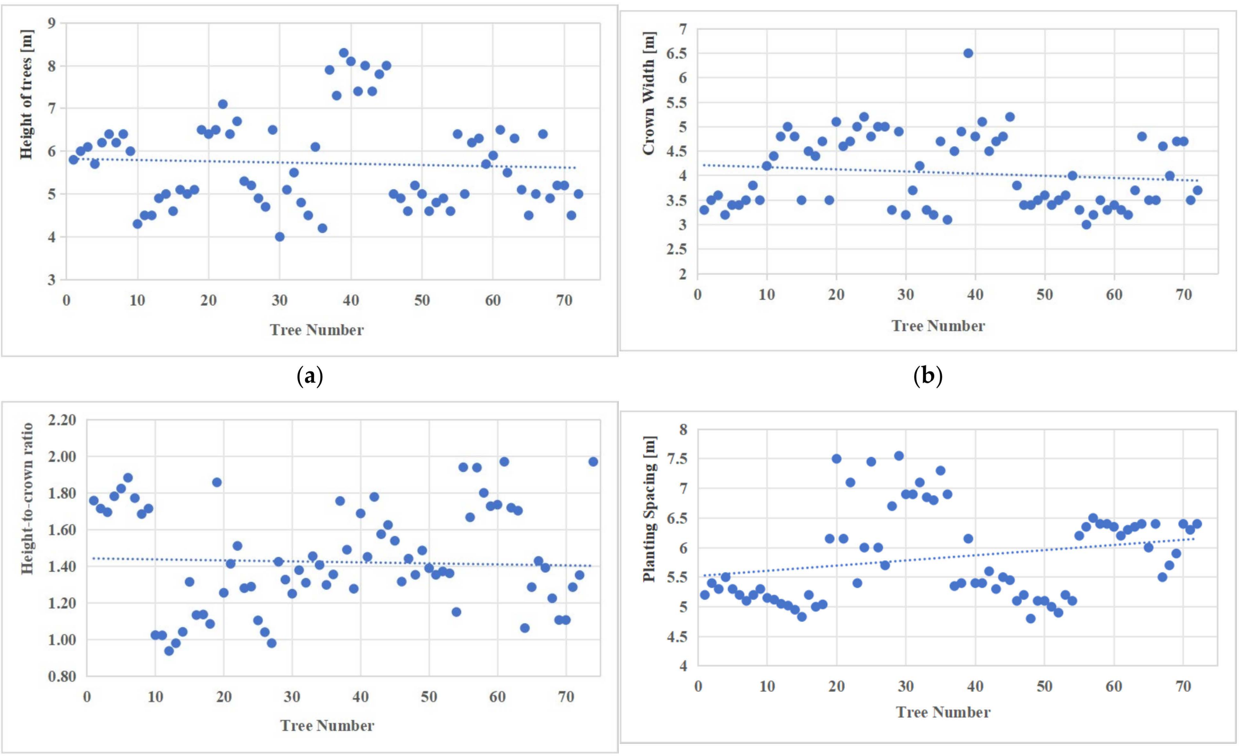
Figure 3. Pingtan Island sample road distribution map.

Figure 4. Sample road Vvegetation on Pingtan Island. (**A**) *Ficus altissima.* (**B**) *Ficus altissima* 'Variegata'. (**C**) *Ficus concinna.* (**D**) *Talipariti tiliaceum.* (**E**) *Araucaria cunninghamii.* (Image source: Plant Plus of China https://www.iplant.cn/, accessed on 13 July 2024).

2.2. Collection, Processing, and Optimization of Basic Data on Street Trees

On 17 October 2023, the survey was carried out. Among the eight principal and subsidiary roads, 24 representative highway sample segments, each measuring about 30 m in length, were chosen, and the sample sites were noted and labelled (Figure 5). This study sampled arborvitae street trees to examine their wind resistance and adaptability under prolonged high-wind circumstances, as damage to street trees in high-wind conditions has a substantial impact on residents' everyday lives. In the field study, the diameter at breast height (DBH), height, width of the crown, and plant spacing of the street trees in the sample roads were measured at a distance of 1.5 m from the trunk to the ground using a Leica rangefinder. The species name was also recorded.

Figure 5. Pingtan Island Road Photos (The pictures are all taken by the author).



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

(**c**) (**d**)

Figure 6. Statistics on street tree planting parameters. (**a**) Height of trees. (**b**) Crown width. (**c**) Height-to-crown ratio. (**d**) Planting spacing. (The dotted line is the average of the vertical coordinates of the plots; The blue dots are the values of the vertical coordinates of the trees).

Street tree data, including height, width of the crown, plant spacing, and other related variables, were counted. The data are shown in Figure 6. The tree height, crown width, plant spacing, height-to-crown ratio thresholds, and medians were then determined. The data are shown in Table 2. The refined data serve as the foundational parameters for the 3D modeling of street trees, which enhances the experiment's viability and scientific validity by more precisely reflecting the traits of nearby street trees.

Table 2. Statistical changes in street tree height, crown width, and height-to-crown ratio.

Parameter Type	Thresholds [m]	Median Value [m]
Height	4.0~8.5	5.7
Crown width	3.0~6.5	4.0
Height-to-crown ratio	0.9~2.0	1.4
Plant spacing	4.8~7.6	5.9

2.3. Experimental Simulation

2.3.1. Wind Environment Simulation

When simulating the transient interference situation of gusty winds on the urban road environment, the computational domain is set to be a rectangular computational domain with a length of 60 m, a width of 25 m, and a height of 30 m. This is because gusty winds move along the direction of the road after entering the urban road environment and is restricted by the street buildings on both sides. The inlet and outlet surfaces are placed at relative places to guarantee that the wind direction created by the airflow in the simulated computational domain is the same as the actual scenario. The level 8 high wind scenario was chosen for simulation because Pingtan Island has numerous days with high winds (greater than level 8) throughout the year. To guarantee that the airflow's wind direction in the simulation domain matches the actual circumstances, the inlet and outlet surfaces are positioned relative to each other. China's official "wind level" standard, which was published in June 2012, states that a level 8 gale is 17.2–20.7 m/s. To test the pressure change after the street tree under the action of the gale, the experiment simulates a level 8 gale, sets the wind speed of the inlet surface to 19 m/s, and places pressure-sensing surfaces on both sides of the wall of the street tree.

2.3.2. Tree Modeling

Only three primary street tree characteristics—tree height, crown width, and spacing—were represented on the 3D model while taking the computational volume into account. AutoCAD 2020 was utilized to create the street trees. Instead of using a street tree, the ball-and-stick model was employed in this experiment. The tree models were imported into the wind field calculation domain and arranged by the direction of the wind field for simulation.

Three optimized factors were used: tree height, crown width, and spacing. Simulations were run for each of the three variables with equal gradient values falling inside the statistical range. In the analysis of the relationship between street tree height, crown width, and wind resistance, the conventional plant morphology-based height-crown ratio of the tree model was determined to be the median value of 1.4, and the field research data indicated that the tree spacing should be the median value of 5.9 m. Six gradients of change were created for the tree heights in the range of 4.0–8.5 m: 4.0 m, 4.9 m, 5.8 m, 6.7 m, 7.6 m, and 8.5 m; they corresponded to the crown widths of 2.9 m, 3.5 m, 4.1 m, 4.8 m, 5.4 m, and 6.0 m, respectively. The tree model height-crown ratio was set to a median value of 1.4 in the investigation of the relationship between plant spacing and wind resistance of street trees, and the height was taken as the median value of 5.7 m. Five gradients of change in the range of 4.8–7.6 m were put up to imitate the plant spacing: 4.8 m, 5.5 m, 6.2 m, 6.9 m, and 7.6 m. Next, the tree model was simulated with a height of 5.7 m, a plant spacing of 4.8–7.6 m, and a height ratio of 1.4.

The tree model height-crown ratio was chosen at the median value of 1.4, the height at the median value of 5.7 m, and the spacing at the median value of 5.9 m, taking into account the common form of column planting and the height of lower shrubs as variables. The simulation was run by setting the spacing of two rows of planting at 2.0 m, four rows at 4.0 m, six rows at 6.0 m, and three rows at 8.0 m, respectively, to examine the relationship between row spacing and column planting and the wind resistance of the street trees. Lower shrub heights were found to hurt street tree wind resistance. The height-crown ratio of the tree model was set at 1.4, the height at 5.7 m, and the plant spacing at the median value of 5.9 m. For the modeling of the compounding structure, the lower shrub heights of 50 cm, 100 cm, and 200 cm, respectively, were put up.

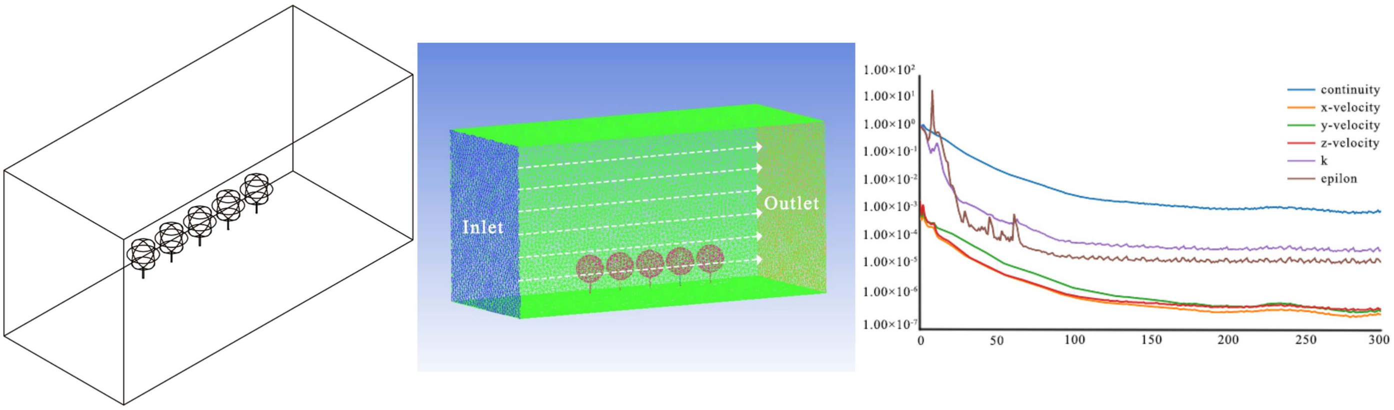
2.3.3. Numerical Simulation and Refinement

The entire model is meshed by setting the inlet, exit, and wall surfaces of the computational domain to mesh when the model is imported into ANSYS's ICEM CFD interface. To improve the accuracy of the simulation, a maximum grid size of 0.8 m × 0.8 m × 0.8 m is selected when gridding using the uniform structured grid technique.

Compared to other turbulence models, it has been demonstrated that the standard k-epsilon model has a stronger connection with the wind field data in numerical simulations of the wind environment [16]. To ensure that the simulation results are within the acceptable range of error, after importing the model grid into the Ansys Fluent interface, set the turbulence model as the standard k-epsilon model. The data are shown in Table 3. Then, set the tree model material as wood, set the wind speed at the inlet surface to 19 m/s, set the number of iterations to 300, and set the data convergence accuracy to 10^{-4}. To generate the results, the results were finally loaded into the CFD POST interface. This case is depicted in Figure 7.

Table 3. Parameter setting for simulation calculation.

Turbulence Model	Standard k-Epsilon Model
Differential method	Headwind difference method
Coupled pressure–velocity solution	SIMPLE arithmetic
Air-fluid state	Ideal, non-compressible



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

Figure 7. Ansys Fluent modeling process. (**a**) CAD modeling schematic. (**b**) Mesh building schematic. (**c**) Residual analysis plot.

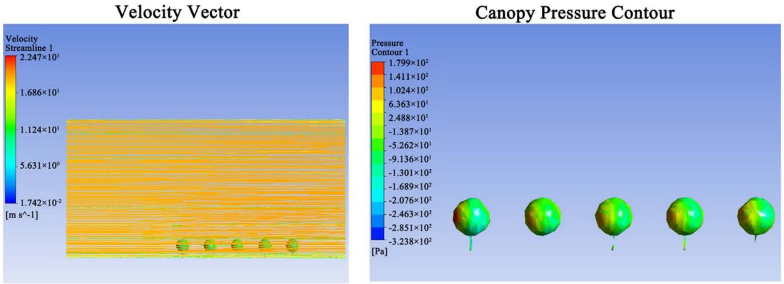
3. Data Simulation Analysis

3.1. Analysis of the Impact of Street Trees of Different Heights on the Wind Environment of Roads

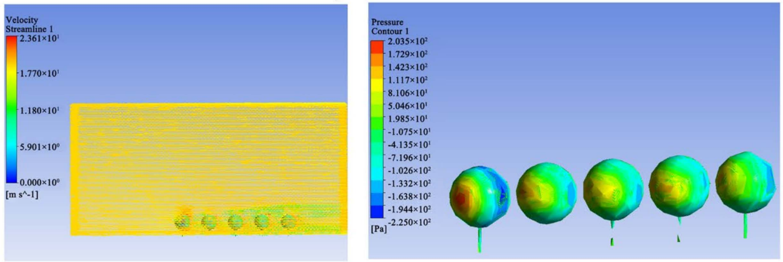
The street trees' height and crown breadth are correlated with the changes in wind speed that occur when strong winds cross over a road. In the same wind circumstances, (1) little trees (4.0 m or less) will not be able to block much wind. Small trees, blooming shrubs, and low plants placed in the center dividing zone of several metropolitan main roadways were hardly able to stop the wind, nor would they lessen its power or speed as it passes by. (2) When a tree's height is less than 6.0 m, its crown widens in proportion to its height; yet, the space between its crown and the crowns of other trees is great, making it impossible for the two to create a shield. A distinct local wind field developed around a single tree, and the motion of the trees was more turbulent. The trees in front of it hardly provided any protection for the last tree, which was experiencing a constant increase in wind speed on its leeward side. The first tree on the windward side was under the strongest pressure, and the wind speed on the leeward side of its canopy was significantly enhanced. In contrast, the other trees' canopies had varying degrees of pressure. (3) When the height of the tree increases to 8.5 m, the tree crown width is about 6.0 m, the ratio of crown width to spacing is about 1.0. With the increase in tree height, the distance between the tree crowns gradually decreases, and the trees in front of the trees behind the trees gradually form a protective effect. The wind band above the street tree has an obvious weakening tendency and, below the tree crowns, it forms a certain degree of wind-sparing channels, in addition to the formation of overall green belts behind the street tree clear zone where wind speed is decreasing. (4) Street trees' wind-blocking effect has a greater effect on the computational domain's overall wind environment, and the turbulent activity there displays a disordered state; however, as tree height increases, so does the maximum wind speed on the outflow side and the maximum pressure on the tree crown. The data are shown in Table 4 and Figure 8.

Table 4. Statistics of simulated data under high wind conditions for different heights of street trees.

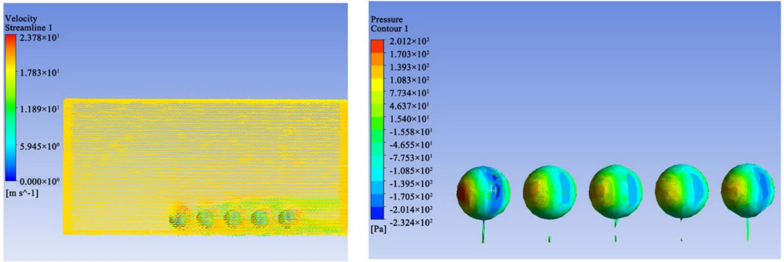
Plant Height [m]	Maximum Wind Speed at the Outlet [m/s]	Maximum Wind Speed in the Area [m/s]	Maximum Pressure on the Crown [Pa]	Minimum Pressure on the Crown [Pa]	Maximum Pressure on the Surface [Pa]	Minimum Pressure on the Surface [Pa]
4.00	17.43	29.43	198.67	−465.49	78.91	−259.61
4.90	17.53	28.18	215.36	−311.65	84.13	−230.36
5.80	17.68	27.39	216.97	−323.87	89.90	−111.92
6.70	18.89	32.56	232.06	−506.96	104.26	−168.02
7.60	18.76	28.25	228.26	−405.56	89.39	−175.46
8.50	17.80	29.41	229.32	−541.29	111.43	−227.42



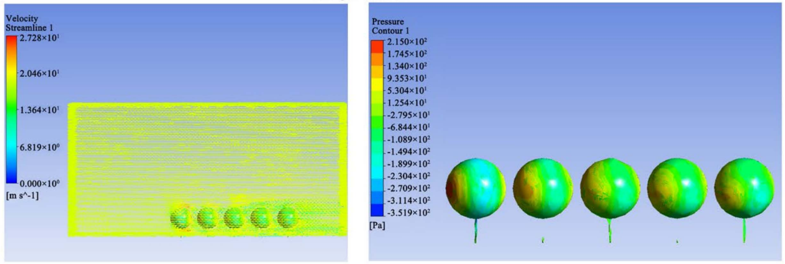
Height 4.00 m



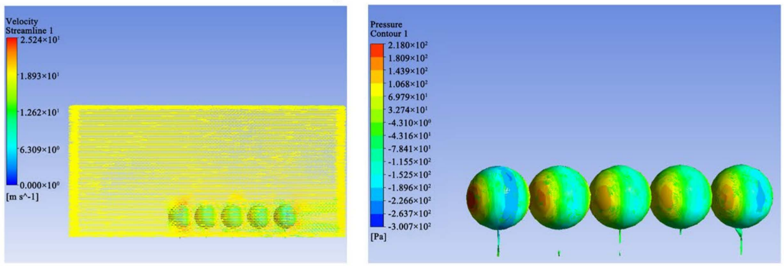
Height 4.90 m



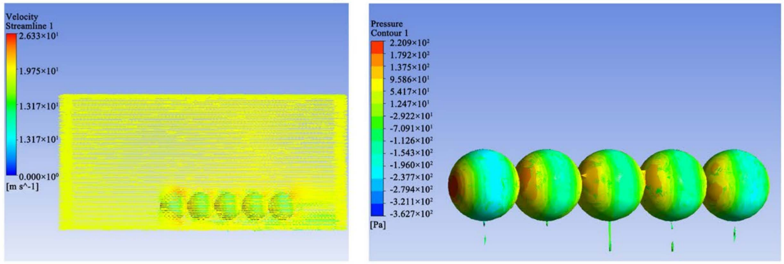
Height 5.80 m



Height 6.70 m



Height 7.60 m



Height 8.50 m

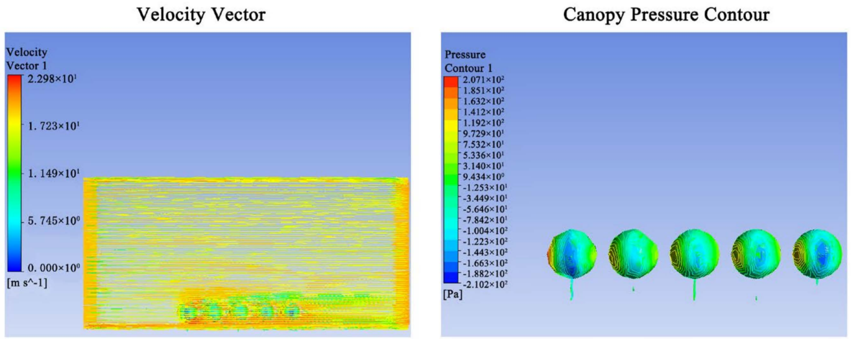
Figure 8. Simulation results under high wind conditions for different heights of street trees.

3.2. Analysis of the Impact of Street Trees with Different Plant Spacings on the Wind Environment of Roads

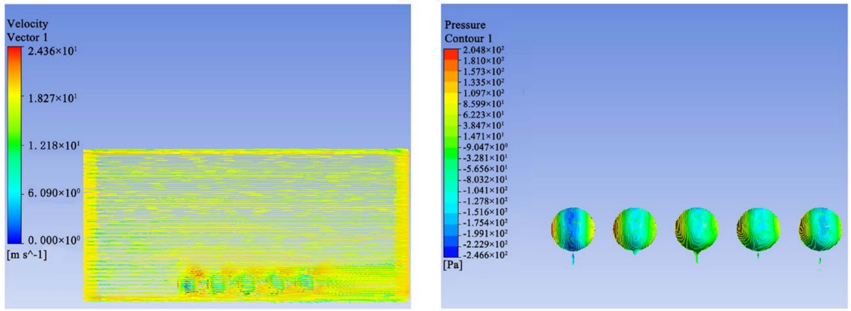
There is a relationship between the distance between street tree plantings and the variation in wind speed during high winds. The wind speed at the top of the first tree was higher, and the wind speed at the top of the second tree gradually declined along with the gradual weakening of the wind pressure on the second tree, under the same wind conditions: (1) When the plant spacing was 4.8 m, the orange-red patch in the middle of the latter tree's crown on the canopy pressure map steadily shrank in comparison to the former, indicating that the former tree provided shelter for the latter during strong winds. The street trees have been planted more densely, forming a clearer wind-sparing path beneath their green belt. (2) In comparison to a plant spacing of 4.8 m, a plant spacing of 5.5 m is nearly in line with the tree's height. This results in an increase in wind speed at both the top and bottom of each tree's canopy, the formation of a clear zone behind the final tree, and the greatest reduction in maximum wind speed on the windward side of the wind at this particular moment. (3) As plant spacing increases, the distance between street trees grows, the former tree's protective effect on the later tree gradually wanes, the force of high winds on the later trees increases, wind speed above the street trees increases and then decreases in a more regular wind speed band, and the trees' relative pressure is maintained. (4) The local wind field surrounding the trees is noticeably strengthened and the area of the wind speed reduction zone at the back of the street tree green zone is noticeably reduced when the plant spacing reaches 7.6 m. At this point, the distance between the street trees is significantly larger than the tree crowns (tree height 5.7 m, crown width 4.0 m, and height-crown ratio of approximately 1.4). When paired with the wind speed vector diagram, it is possible to observe that the wind speed band above the street tree's green zone also showed a tendency to weaken and that the turbulence activity tended to be regular. In contrast to the previous scenario, when the plant spacing did not reach 7.6 m, the orange-red pressurized area in the center of the tree crown expanded with the increase in plant spacing. As the plant spacing increases and becomes significantly larger than the tree crown, it is evident that the former tree no longer serves as a windshield for the latter, each street tree's wind condition during strong winds is nearly identical to that of a single tree, and no street tree blocks strong winds as a whole. The data are shown in Table 5 and Figure 9.

Table 5. Statistics of simulated data under high wind conditions for different spacings of street trees.

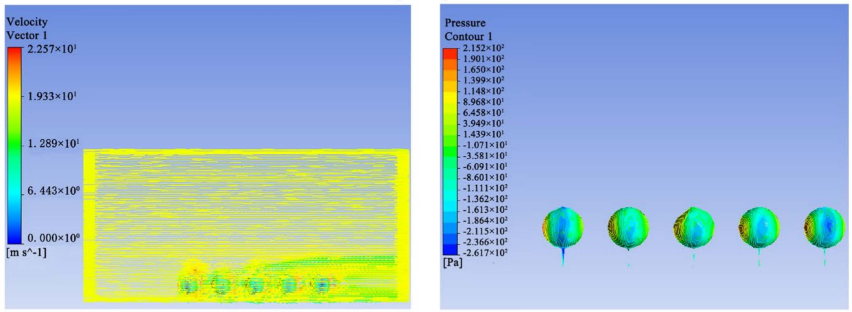
Plant Spacing [m]	Maximum Wind Speed at the Outlet [m/s]	Maximum Wind Speed in the Area [m/s]	Maximum Pressure on the Crown [Pa]	Minimum Pressure on the Crown [Pa]	Maximum Pressure on the Surface [Pa]	Minimum Pressure on the Surface [Pa]
4.80	18.72	35.97	218.79	−275.17	167.53	−203.82
5.50	17.66	32.87	223.48	−433.68	125.35	−243.23
6.20	17.88	34.98	221.32	−482.16	121.80	−198.49
6.90	18.65	36.56	219.43	−346.91	136.21	−141.70
7.60	18.87	42.52	224.06	−425.96	118.54	−242.85



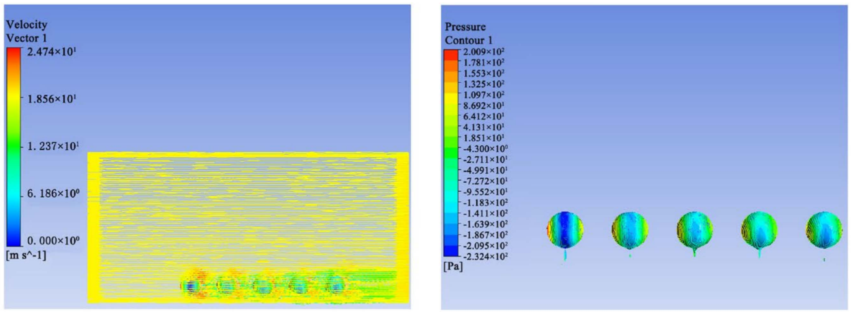
Plant spaing 4.80 m



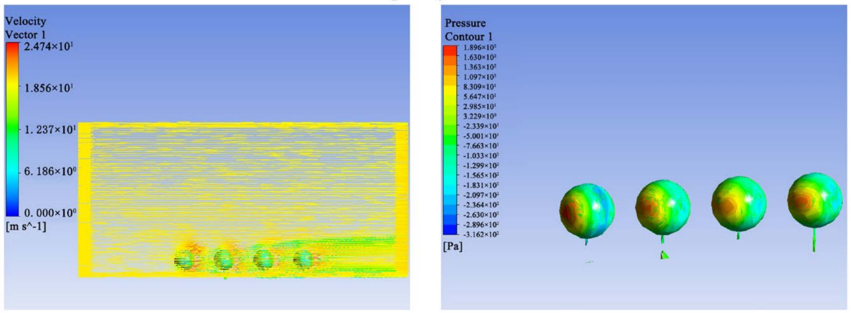
Plant spacing 5.50 m



Plant spacing 6.20 m



Plant spacing 6.90 m



Plant spacing 7.60 m

0 15.0 30.0 m
7.5 22.5

0 5.0 10.0 m
2.5 7.5

Figure 9. Simulation results under high wind conditions for different spacing of street trees.

3.3. Analysis of the Impact of Street Trees with Different Row Spacings on the Wind Environment of Roads

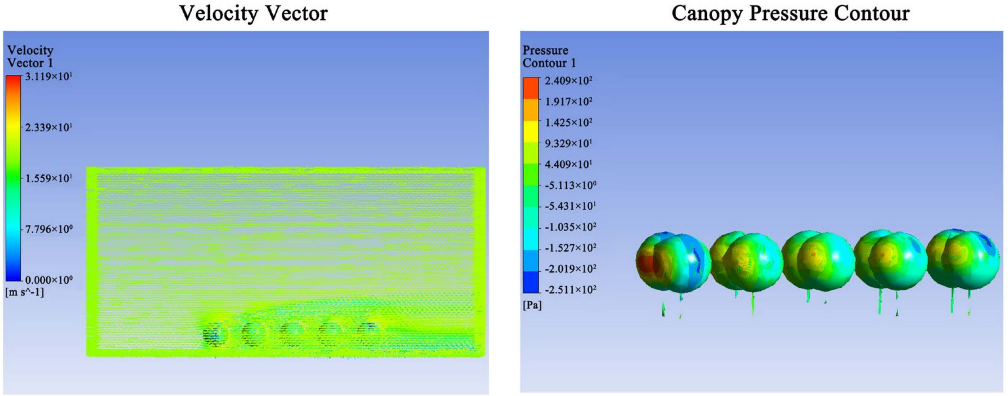
3.3.1. Analysis of the Impact of Street Trees Planted in Double Rows with Different Spacings on the Wind Environment of Roads

There is a relationship between the planting style and row spacing of street trees and the variation in wind speed that occurs when strong winds blow across them. Thus, the impacts of planting street trees in double- and triple-rows with varying row spacings on the wind environment of roadways are further examined in this research.

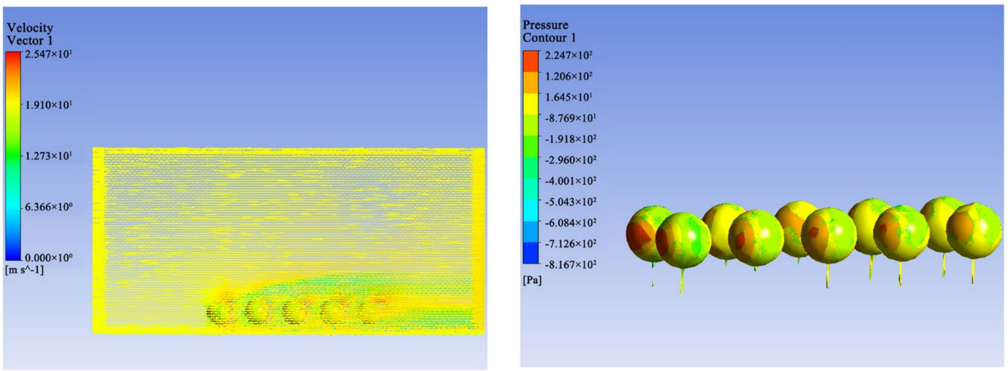
Under identical wind conditions, (1) two rows of trees with canopies that overlap by 2.0 m can be considered as a single unit. The street trees in front of the trees in the back of the trees contribute to protecting the back of the trees by the significantly weakened pressure; the surrounding wind speed decreases; and the street trees above the formation of the first increase and then decrease in the wind speed deceleration zone. The first two street trees are on the windward side of the stronger pressure, which results in a larger top wind speed. (2) When the row spacing is 4.0 m, two rows of trees in the canopy are in the tangent state, with the row spacing of the column planting and tree crown width being the same (tree height of 5.7 m, crown width of 4.0 m, and the height-crown ratio of roughly 1.4). In comparison to the row spacing of 2.0 trees in column planting, the overall domain of the overall wind speed increases. For the first two trees, in the center of the crown, the orange-red pressurized area increases significantly, and the rear of the center of the tree crown also appears within a certain range of orange-red. Above the trees, an increase of and then a reduced wind velocity deceleration zone is more obvious, and this scenario is a more significant weakening of the maxim. The wind speed deceleration zone above the rows of trees grows and subsequently decreases more visibly within a specific range of orange-red, and the weakening of the maximum wind speed on the windward side is more important in this scenario. (3) As row spacing increases gradually, there is a complex turbulent movement between rows, a more similar orange-red pressure zone at each tree's canopy center, less protection from the front trees for the rear trees, an increase in the force of high winds on the rear trees, and a gradual reduction in the range of the wind speed reduction zone above the street trees. (4) The two rows of trees are farther apart when the row spacing is 8.0 m, which is twice the crown width. Above the wind speed reduction zone, the street trees clearly narrow to a single row of planting columns according to the wind situation, and the trees surrounding the wind speed are clearly strengthened. The data are shown in Table 6 and Figure 10.

Table 6. Simulated statistics of street trees planted in double rows with different spacings under high wind conditions.

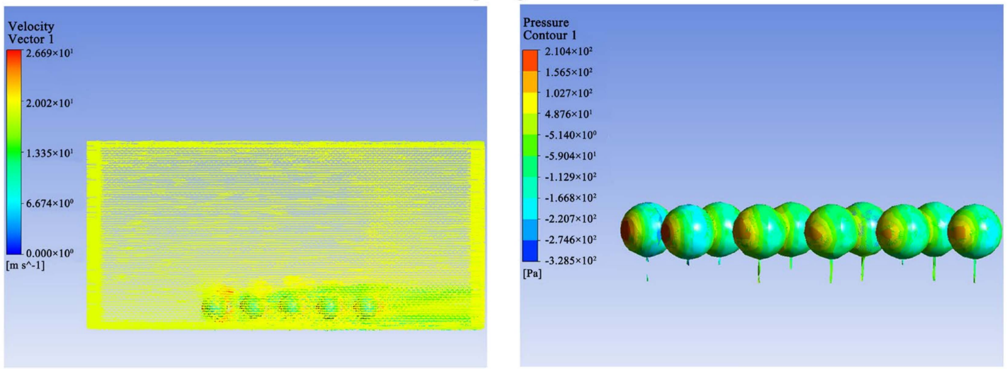
Row Spacing [m]	Maximum Wind Speed at the Outlet [m/s]	Maximum Wind Speed in the Area [m/s]	Maximum Pressure on the Crown [Pa]	Minimum Pressure on the Crown [Pa]	Maximum Pressure on the Surface [Pa]	Minimum Pressure on the Surface [Pa]
2.00	18.44	39.99	244.60	−342.98	131.35	−287.14
4.00	17.55	38.82	255.02	−581.83	97.77	−259.08
6.00	17.65	36.18	240.52	−440.88	91.01	−231.12
8.00	18.05	33.09	223.39	−526.55	62.35	−241.77



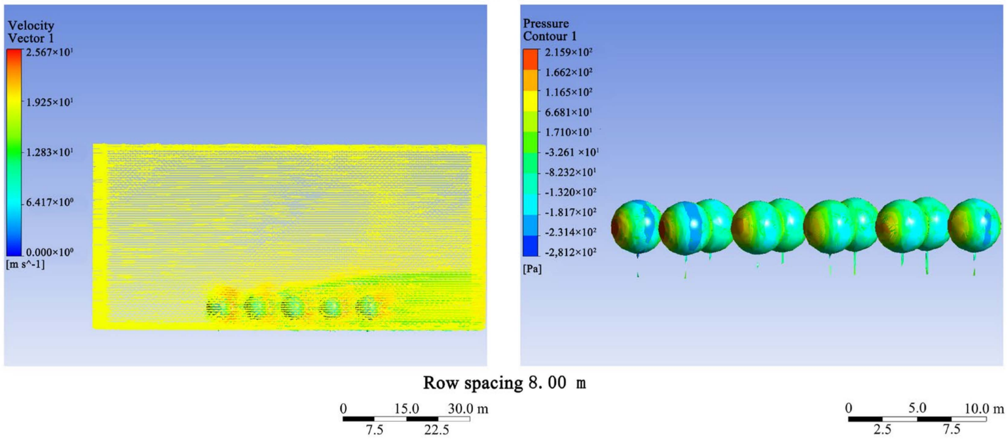
Row spacing 2.00 m



Row spacing 4. 00 m



Row spacing 6. 00 m



Row spacing 8. 00 m

Figure 10. Simulation results under high wind conditions for street trees planted in double rows with different spacings.

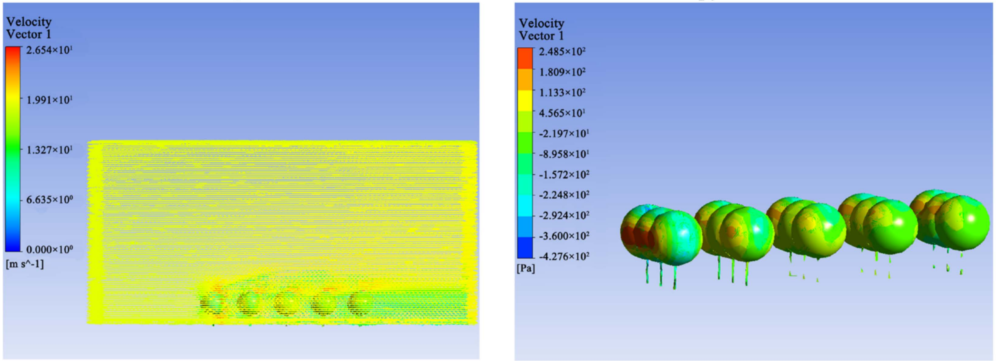
3.3.2. Analysis of the Impact of Street Trees Planted in Three Rows with Different Spacings on the Wind Environment of Roads

The first three street trees' crowns overlap to form a range of wind-resistant barriers under the same wind conditions: (1) When the row spacing is 2.0 m for three rows of planting, the tops of these trees' wind speed is significantly increased, which protects the rear trees; additionally, an obvious wind speed deceleration zone is formed at the leeward side of the street trees' green belt. (2) The wind speed around the trees is increased, the wind speed deceleration zone at the leeward side of the tree belt gradually disappears, a wind speed deceleration zone is formed above the street trees that first increases and then decreases, and a certain range of wind-sparing channels is formed below the tree crowns. (3) When the row spacing is 4.0 m, the crowns of the trees in each row are tangent, and the turbulent activity between rows increases compared with the row spacing of 2.0 m. Tunnels underneath the tree canopy save on wind. The protective effect of the trees in front of the trees in the back is gradually diminished as row spacing increases. Additionally, the wind speed surrounding each street tree increases, its pressure situation tends to be similar to that of a single tree under high winds, and the range of the wind speed reduction zone above the street tree decreases. (4) When the row spacing is 8.0 m (tree height 5.7 m, crown 4.0 m, and height-crown ratio of about 1.4), the range of the wind speed reduction zones above the street tree is significantly reduced, the wind field around the trees is significantly strengthened, and the overall wind situation is more similar to the wind situation under the gale with a single row of planted street trees. The data are shown in Table 7 and Figure 11.

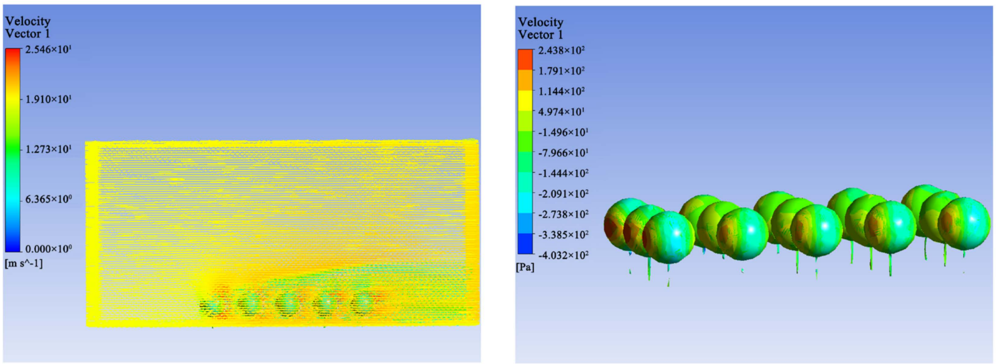
Table 7. Simulated data of street trees planted in three rows with different spacings under high wind conditions.

Row Spacing [m]	Maximum Wind Speed at the Outlet [m/s]	Maximum Wind Speed in the Area [m/s]	Maximum Pressure on the Crown [Pa]	Minimum Pressure on the Crown [Pa]	Maximum Pressure on the Surface [Pa]	Minimum Pressure on the Surface [Pa]
2.00	18.65	52.69	255.39	−684.30	146.80	−373.73
4.00	17.91	51.99	253.68	−617.42	91.53	−297.29
6.00	18.58	47.03	246.34	−492.28	121.72	−205.82
8.00	18.89	33.69	256.18	−559.12	102.99	−327.93

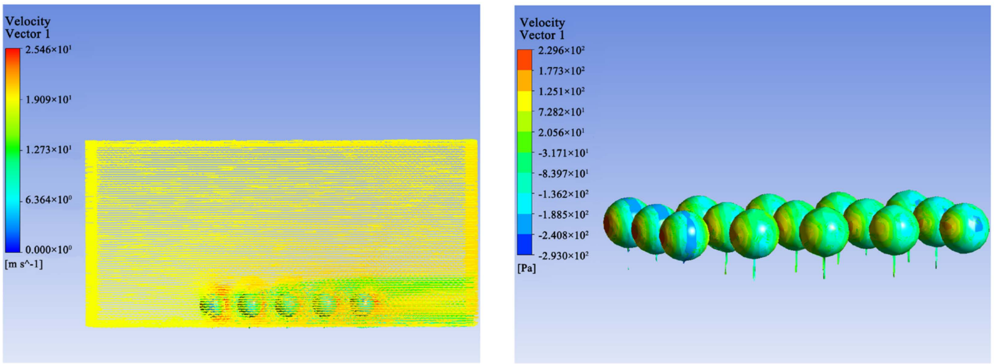
Velocity Vector Canopy Pressure Contour



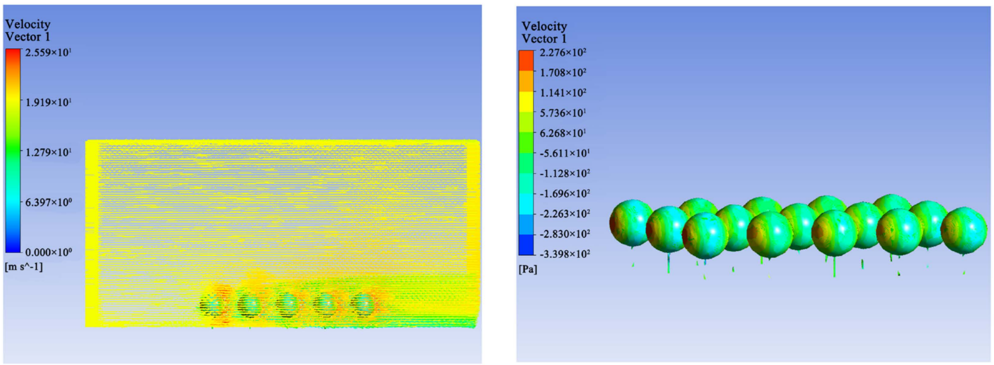
Row spacing 2.00 m



Row spacing 4.00 m



Row spacing 6.00 m



Row spacing 8. 00 m

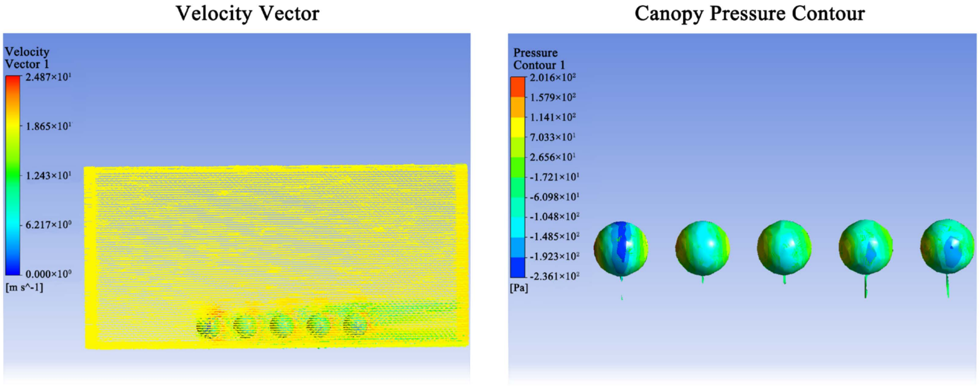
Figure 11. Simulation results under high wind conditions for street trees planted in three rows with different spacing.

3.3.3. Analysis of the Impact of Street Trees with Different Lower Shrub Heights on the Wind Environment of the Roadway

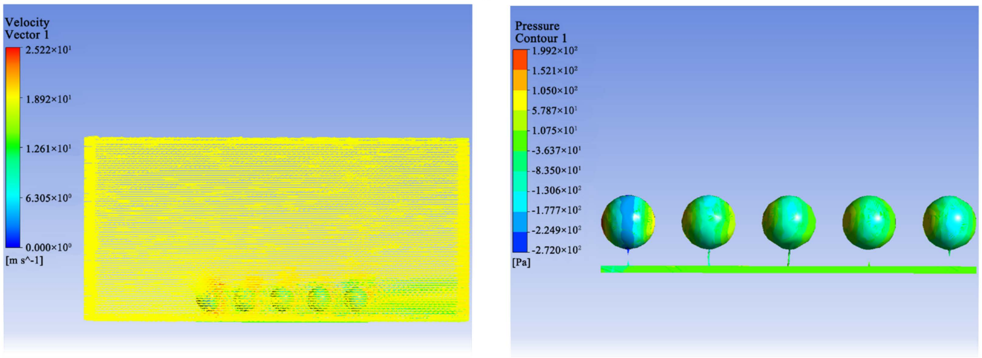
There is a relationship between the change in wind speed during high winds and the height of bushes in the lower layers of street trees. Under the same wind conditions: (1) when the height of the lower shrubs is 0.5 m, the wind speed is stronger at the top of the first tree, the wind speed at the top of the trees in the rear gradually decreases, the trees in the front play a role in wind blocking compared with the case of no shrub planting, the orange-red strong wind area around the trees decreases, and there is a clear green weak wind area below the street trees. (2) When the lower shrubs are 1.0 m high, the maximum pressure exerted on the canopy is the greatest at this time, the turbulent activity between the trees is gradually complicated, the wind speed at the top of each street tree is increased across the board, and the protective effect of the trees in front of the trees in the back of the tree is weakened. (3) As the height of the lower shrubs increases, the contact area between the shrub layer and the wind increases, the maximum wind speed in the domain gradually decreases, and the wind speed deceleration zone above the street tree gradually moves back to the rear of the tree belt, while the green weak wind zone below it continues to expand, indicating that the planting of the lower shrubs has a certain weakening effect on the wind passing through the street tree. The street tree below the formation of the wind channel cannot be thinned, the orange-red strong wind area surrounding the tree is remains more noticeable, and the height of the lower shrubs does not reach the height of 2.0 m compared to the case of the trees in front, weakening of the role of the wind blocker. At this point, the height of the shrubs is higher than the height under the branches of the street tree (tree height 5.7 m, crown width 4.0 m, height under the branches 1.7 m, and height-crown ratio of approximately 1.4). Behind the tree belt, the area of the green weak wind region shrank. The data are shown in Table 8 and Figure 12.

Table 8. Statistics of simulation data under high wind conditions for street trees with different lower shrub heights.

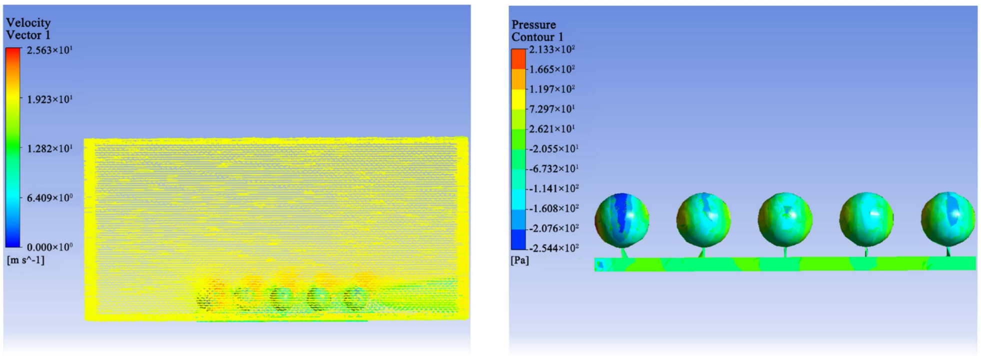
Shrub Height [m]	Maximum Wind Speed at the Outlet [m/s]	Maximum Wind Speed in the Area [m/s]	Maximum Pressure on the Crown [Pa]	Minimum Pressure on the Crown [Pa]	Maximum Pressure on the Surface [Pa]	Minimum Pressure on the Surface [Pa]
0.00	18.88	32.40	208.32	−345.87	43.65	−230.50
0.50	18.53	31.20	205.23	−388.36	200.37	−134.68
1.00	19.10	29.65	224.87	−341.41	217.79	−213.78
2.00	18.70	29.64	213.76	−287.87	78.13	−259.89



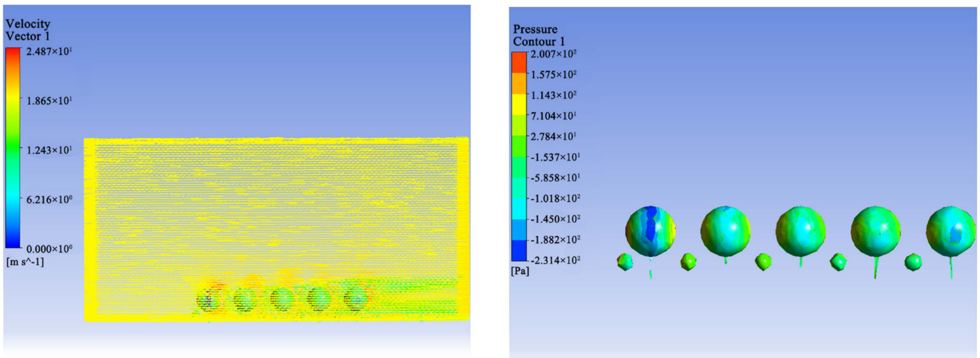
Shrub height 2.00 m



Shrub height 4.00 m



Shrub height 6.00 m



Shrub height 8.00 m

Figure 12. Simulation results under high wind conditions for street trees with different lower shrub heights.

4. Discussion

(1) Fluent experiments with simulated wind fields have revealed that street trees with different planting conditions exhibit varying wind resistance properties. Street trees'

wind resistance is influenced by factors connected to tree planting; this resistance is not solely defined by one indicator but rather by a combination of related indicators. Tree wind resistance has been linked to planting factors including tree crown width and diameter at breast height, according to prior studies in the literature that used field research and empirical analysis [23,24]. Through tension experiments, Nguyen TM ascertained the wind stability of trees and, using the Cox regression model and the generalized linear mixed model, argued that tree variables (tree species, size and height, etc.) had a substantial effect on tree stability [25]. Following the typhoon disaster, Wu Xiankun collected data on tree morphological indexes through a field survey. Using principal component analysis and cluster analysis, she discovered that tree crown density and width are the primary influencing factors affecting a tree's ability to withstand wind [26], which is in line with the findings of this paper. By selecting the proper planting parameters for street trees, one can optimize their ability to block wind, safeguard the preceding tree in the tree protection role, lessen wind caused by tree fracture or collapse and other hazards, and enhance the stability of the wind environment of the roadside green space. Street trees exhibit varying pressure situations depending on the planting parameters chosen.

(2) This is demonstrated by simulating the stress under strong winds on street tree strips with varying heights, crown widths, and spacing: Planting trees or shrubs below 4.0 m has less of an impact on blocking gales; street trees should be planted between 6.0 and 9.0 m in height. Street trees with morphological traits that are not conducive to wind resistance, such as excessive height, large crowns, dense branches and leaves, shallow root systems, and a high center of gravity, are more likely to break their trunks or topple over in windy conditions. The findings of research conducted by Yu Guangcan on garden trees following Typhoon Mangosteen in Guangzhou [27], Zhang Deshun on the wind resistance of garden trees in the coastal area of Shanghai [7], and Xiao Jieshu on garden trees following Typhoon Vicente in Shenzhen [23], all support this. The results are consistent. In order to maintain normal tree growth, the roadside green belt's wind resistance, and the appearance of a green landscape, the plant spacing should be no less than 1.0 times the crown width and no more than 1.75 times the crown width. This adjustment must be made based on the height and crown width of the roadside trees. Too little distance between trees makes the crowns connected and prevents the subterranean root systems from having enough room to expand and support the above-ground portion of the tree, which improves stability and makes street trees less resilient to strong winds [28]. The previous Fluent simulation findings indicate that when the street trees are farther apart and the plant spacing is significantly greater than the crown width, each tree's wind exposure during strong winds is almost identical to that of a single tree, and there is no street tree belt to shield the strong winds.

(3) Under strong wind conditions, trees undergo deformation and bending, resulting in a complicated wind field surrounding the tree due to the change in canopy shape. The majority of studies on wind-induced stresses on trees are consistent with the result that, under high wind circumstances, the pressure on a single tree increases with increasing wind speed [8,29,30]. Since there are not many studies on the stresses caused by mutual interference between rows of trees, this paper adds the simulation scenarios of two and three rows of planting under strong winds. The studies mentioned above, however, focus on the stresses of single trees or single rows of planting under strong winds. The findings indicate that two rows of street trees are more useful and wind-resistant than three rows, and that a distance of 2.0 to 6.0 m between rows is more suitable. When planting with too much space between rows, the pressure conditions under strong winds are comparable to those of single-row planting, making it impossible to maximize the wind-resistant impact.

(4) The "shrubs + trees" multi-layer structure is crucial to the wind resistance and visual impact of roadside green belts. The street tree's main portion is its crown, which is

strengthened by its dense branch and leaf structure to withstand strong winds. The under-branch portion of the tree, on the other hand, is only made up of the trunk and lacks any branches or leaves. This creates a wind-sparing channel beneath the tree as the wind speed increases. To protect the street tree's trunk and reduce wind speed in the under-branch portion, small trees or shrubs of the right size should be planted [31]. The height of the lower shrubs should be chosen to be lower than the height of the first branch of the arborvitae roadside trees, with 0.5~1.0 m being a more suitable height, according to the findings from Fluent's simulations of the road's wind environment. The lower shrubs can offer some protection to the tree trunks when the trees have not grown to the necessary height, and the arrangement of the trees in the compound structure also reduces wind speed.

(5) Due to the special geographic location and climatic conditions of Pingtan Island, as well as the many practical problems faced in greening construction, the future greening construction of Pingtan Island is a constantly changing long-term infrastructure project. Previous studies have established a grading system for wind-resistant tree species in coastal towns based on field surveys and data analysis following typhoons such as Typhoon Moranti in Xiamen, Typhoon Swan, and Typhoon Paka in Zhuhai. A grading system for tree species is proposed: wind-resistant tree species represented by *Roystonea regia*, *Syagrus romanzoffiana*, *Acacia confusa*, *Phoenix sylvestris*, and *Ficus altissima*, and so on; moderately wind-resistant tree species represented by *Casuarina equisetifolia*, *Cinnamomum septentrionale*, *Chukrasia tabularis*, and *Terminalia neotaliala*; and *Jacaranda mimosifolia*, *Bombax ceiba*, and *Bauhinia variegata* as less wind-resistant [32–34]. To create an island cityscape boulevard with high stability, it is recommended to retain the strong wind-resistant native tree species, primarily *Casuarina equisetifolia*, *Acacia confusa*, and *Phoenix sylvestris*, and to increase the planting of palm species, such as *Roystonea regia*, *Syagrus romanzoffiana*, *Livistona chinensi*, *Washingtonia filifera*, and *Phoenix canariensis*. The monsoon environment causes extremely irregular turbulence movements, and there is no discernible pattern of strong wind movement on the road greens, making the general greening of Pingtan Island difficult due to wind stability. In addition to regional climatic conditions and relevant planting parameters, the strength of wind resistance of street trees is affected by factors such as the depth of the tree's root system [35], the wood properties of the trunk [36], the morphological characteristics of the crown [37], and stand conditions [38].

5. Conclusions

The wind environment of eight main and secondary roadways on Pingtan Island was examined and debated using field research and Fluent simulation technology. The height, crown width, and spacing of the trees all affect how wind-resistant the trees are while planting street trees. The degree of wind damage to street trees can be significantly decreased, the total wind resistance of the road plant landscape can be improved, and the resilience of urban green space to wind damage can be increased by choosing planting parameters that are appropriate. The software simulation experiment yielded the following conclusions:

(1) Street trees should not be too tall to prevent giant trees from breaking their trunks or falling down. It is recommended that roadway trees stand between 6.0 and 9.0 m tall.
(2) Street tree planting spacing should vary according to height and crown width. Tree spacing should be at least 1.0 times the crown width but no more than 1.75 times the crown width.
(3) The planting form for street trees should be modified based on the width and level of the road. To optimize the amount of green space along main and minor roads for wind performance, street tree planting can be done in double rows spaced 2.0 m to 6.0 m apart.

Previous studies were all simulated studies on the stresses of single trees or single rows of trees in high winds, and there is a scarcity of research on the stresses of trees interfering with one another between rows. Additionally, multi-row planting is a successful windproof planting technique when it comes to windy urban street trees or green barrier planting. Therefore, this article includes simulations of two-row and three-row tree planting forms under high wind conditions. The impacts of common street tree planting methods on tree wind resistance and road wind environment are explored. Suggestions and references are provided for designing road planting landscapes on Pingtan Island and other wind-prone areas.

The simulation experiment was an exploratory one. Wind exposure of street trees was simulated using various planting conditions in an ideal and scientific experimental environment. The wind resistance of street trees will be influenced by various factors in the actual wind field, including tree canopy density, branch structure, root distribution, and urban climate characteristics. Nevertheless, the results of this study are limited because the current simulations are not able to satisfy all parameter settings. The experiment was only carried out for field research and numerical modeling on islands with a subtropical marine monsoon climate. The study's findings are somewhat significant in that they provide guidance for choosing street tree planting patterns in frequent, windy situations. However, it is important to investigate if the wind condition of street trees will vary under various climatic conditions and vegetation kinds. We will integrate this research with other models to build a more precise model for useful planting recommendations in the future.

The process of enhancing the wind resistance of road green landscapes is a lengthy and dynamic one. To attain optimal wind stability, it is necessary to modify plant spacing appropriately and deploy low shrubs and trees in different configuration stages. The enhancement of the wind resistance of road greens on Pingtan Island can be started from three aspects: planning and design, construction and planting, and greening management.

In terms of planning and design, street trees are chosen for their deep roots and resistance to wind. As much as practicable, they should be planted in column-planted ribbon landscaping, with plant spacings of 1.0 to 1.75 times the crown width and row spacings of 2.0 m to 6.0 m; avoid the appearance of tree pools planted with only one tree; maintain a certain size of tree pool area and use permeable paving for adjacent roads as much as possible to allow for adequate root growth of street trees; and plant low shrubs at a height of 0.5–1.0 m to create a stable road plant ecosystem.

In terms of construction and planting, attention should be paid to the quality of seedlings and soil ball specifications, as well as ensuring the quality and space of the soil in the tree pool to ensure the healthy growth of the seedlings. The growing conditions of seedlings are related to the health of their trees, and the wind resistance of street trees is related due to their health. Factors such as soil, water, fertilizer, pests, and diseases all affect tree health. Construction and planting should focus on loose and permeable soil, balanced water and fertilizer, and pest and disease control.

In terms of greening management, it is emphasized that regular pruning and maintenance will help street trees form an ideal wind-resistant structure. Tree heights of 6.0 m to 9.0 m are appropriate. For tree species with greater heights or faster growth rates such as *Pinus massoniana*, *Eucalyptus robusta*, and *Bauhinia purpurea*, regular crown thinning and top pruning should be carried out to cultivate wind-resistant tree structures and to avoid trees from breaking their trunks or collapsing. For shallow-rooted tree species with dense crowns such as *Ficus concinna* and *Talipariti tiliaceum*, pruning should be strengthened to avoid large crowns that attract wind and to improve the overall wind-resistant performance of roadside trees in terms of maintenance and management.

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Informed Consent Statement: This study does not involve humans.

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References

1. Toparlar, Y.; Blocken, B.; Maiheu, B.; van Heijst, G.J.F. A review on the CFD analysis of urban microclimate. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1613–1640. [CrossRef]
2. United Nations Office for Disarmament Affairs. *World Urbanization Prospects: The 2018 Revision*; United Nations: New York, NY, USA, 2019.
3. Yang, S.W.; Wang, L.Z.; Stathopoulos, T.; Marey, A.M. Urban microclimate and its impact on built environment—A review. *Build. Environ.* **2023**, *238*, 110334. [CrossRef]
4. Zhuang, X.L.; Duan, Y.X.; Jin, H.X. Research Review on Urban Landscape Micro-climate. *Chin. Landsc. Archit.* **2017**, *33*, 23–28.
5. Mullaney, J.; Lucke, T.; Trueman, S. A review of benefits and challenges in growing street trees in paved urban environments. *Landsc. Urban Plan.* **2015**, *134*, 157–166. [CrossRef]
6. Wong, N.H.; Tan, C.L.; Kolokotsa, D.D.; Takebayashi, H. Greenery as a mitigation and adaptation strategy to urban heat. *Nat. Rev. Earth Environ.* **2021**, *2*, 166–181. [CrossRef]
7. Zhang, D.S.; Li, K.K.; Li, L.L.; Zhang, L.Y.; Liu, M. Wind resistance of 25 landscape tree species in coastal area of Shanghai. *J. Beijing For. Univ.* **2020**, *42*, 122–130. [CrossRef]
8. He, D.Y.; Li, Z.N. Wind tunnel test on wind-induced responses of roadside trees. *J. Nat. Disasters* **2019**, *28*, 44–53. [CrossRef]
9. Amani-Beni, M.; Malazi, M.T.; Dehghanian, K.; Dehghanifarsani, L. Investigating the effects of wind loading on three dimensional tree models using numerical simulation with implications for urban desig. *Sci. Rep.* **2023**, *13*, 7277. [CrossRef]
10. Wang, L.; Su, J.W.; Gu, Z.L.; Tang, L.Y. Numerical study on flow field and pollutant dispersion in an ideal street canyon within a real tree model at different wind velocities. *Comput. Math. Appl.* **2021**, *81*, 679–692. [CrossRef]
11. He, L.J.; Hang, J.; Wang, X.M.; Lin, B.R.; Li, X.H.; Lan, G.D. Numerical investigations of flow and passive pollutant exposure in high-rise deep street canyons with various street aspect ratios and viaduct settings. *Sci. Total Environ.* **2017**, *584*, 189–206. [CrossRef]
12. Chen, L.; Hang, J.; Sandberg, M.; Claesson, L.; Di Sabatino, S.; Wigo, H. The impacts of building height variations and building packing densities on flow adjustment and city breathability in idealized urban models. *Build. Environ.* **2017**, *118*, 344–361. [CrossRef]
13. Wei, Z.; Deng, Y.C.; Zhang, W.; Yang, Z.H.; Feroz, S. An empirical study of two numerical models for wind resource simulation in complex terrain. *Energy Eng. Environ. Eng.* **2014**, *535*, 8. [CrossRef]
14. Buccolieri, R.; Salim, S.M.; Leo, L.S.; Di Sabatino, S.; Chan, A.D.; Ielpo, P.; de Gennaro, G.; Gromke, C. Analysis of local scale tree-atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction. *Atmos. Environ.* **2011**, *45*, 1072–1713. [CrossRef]
15. Amorim, J.H.; Valente, J.; Pirnentel, C.; Miranda, A.I.; Borrego, C. Detailed modelling of the wind comfort in a city avenue at the pedestrian level. *Usage Usability Util. 3D City Models* **2012**, *2012*, 03008. [CrossRef]
16. Hosseinzadeh, A.; Keshmiri, A. Computational Simulation of Wind Microclimate in Complex Urban Models and Mitigation Using Tree. *Buildings* **2021**, *11*, 112. [CrossRef]
17. Li, J.Y.; Liu, J.Y.; Srebric, J.; Hu, Y.M.; Liu, M.; Su, L.; Wang, S.C. The Effect of Tree-Planting Patterns on the Microclimate within a Courtyard. *Sustainability* **2019**, *11*, 1665. [CrossRef]
18. Zeng, F.H.; Simeja, D.; Ren, X.Y.; Chen, Z.G.; Zhao, H.Y. Influence of Urban Road Green Belts on Pedestrian-Level Wind in Height-Asymmetric Street Canyon. *Atmosphere* **2022**, *13*, 1285. [CrossRef]
19. Li, X.J.; Ratti, C.; Seiferling, I. Mapping urban landscapes along streets using google street view. In *Advances in Cartography and GIScience*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 341–356. [CrossRef]
20. Yuan, Y.F.; Ran, M.Y.; Yuan, J.J.; Zhang, L.S. Analytical investigation on the wind environment of Pingtan Island. *Fujian Archit. Constr.* **2016**, *3*, 10–16.
21. Liu, J.X.; He, Y.Q.; Xie, Y.Q.; Wei, K.; Shi, X.J.; Deng, C.Y. Problems and Protection and Development Strategy of Vegetation in Fujian Islands. *For. Inventory Plan.* **2021**, *46*, 157–164.
22. Lin, B.R.; Li, X.F.; Zhu, Y.X.; Qin, Y.G. Numerical simulation studies of the different vegetation patterns' effects on outdoor pedestrian thermal comfor. *J. Wind Eng. Ind. Aerodyn.* **2008**, *96*, 1707–1718. [CrossRef]
23. Xiao, J.S.; Feng, J.H. Research on the Typhoon Resistance Ability of Trees in South China. *Chin. Landsc. Archit.* **2014**, *30*, 115–119.
24. Paz, H.; Vega-Ramos, F.; Arreola-Villa, F. Understanding hurricane resistance and resilience in tropical dry forest trees: A functional traits approach. *For. Ecol. Manag.* **2018**, *426*, 115–122. [CrossRef]
25. Nguyen, T.M.; Fukui, S.; Iwama, S.; Dang, T.T.; Mizunaga, H. Anchorage and stability of three major plantation forest species in vietnam. *J. Trop. For. Sci.* **2021**, *33*, 30–40. [CrossRef]
26. Wu, X.K. *Effect of Typhoon Disasters to Urban Landscape Trees and Typhoon Disaster-Reducing Strategies in Shenzhen*; Nanjing Forestry University: Nanjing, China, 2007.
27. Yu, G.C.; Zhou, G.Y.; Zheng, F. Impacts of Typhoon "Mangkhut" on Trees in Huolushan Forest Park, Guangzhou. *Chin. Landsc. Archit.* **2020**. [CrossRef]

28. Zu, R.C. *Hai Kou Park Selection and Application of Wind-Resistant Garden Plants*; Hainan University: Haikou, China, 2016.
29. Cao, J.; Tamura, Y.; Yoshida, A. Wind tunnel study on aerodynamic characteristics of shrubby specimens of three tree species. *Urban For. Urban Green.* **2012**, *11*, 465–476. [CrossRef]
30. Manickathan, L.; Defraeye, T.; Allegrini, J.; Derome, D.; Carmeliet, J. Comparative study of flow field and drag coefficient of model and small natural trees in a wind tunnel. *Urban For. Urban Green.* **2018**, *35*, 230–239. [CrossRef]
31. Liu, R.J.; Yan, X.Y.; Wang, X. Study on the effect of city greening on wind environment based on CFD modeling technique. *J. Shijiazhuang Tiedao Univ. (Soc. Sci. Ed.)* **2022**, *16*, 104–108.
32. Wang, L.M.; Wang, Z.D.; Xu, H.Y. The investigation and counter measures of landscape trees in the 9914# typhoon in Xiamen. *Chin. Landsc. Archit.* **2000**, *16*, 65–68.
33. Huang, S.Y.; Chen, Z.; Zhou, Y. The Research on the Failure and Rejuvenation of Street Trees after Typhoon 'Hato' and 'Pakhar'. *Guangdong Landsc. Archit.* **2017**, *39*, 91–95.
34. Lin, S.Y.; Zhou, J.Y.; Qin, Y.F.; Dong, J.W. The Influence of Typhoon Meranti on the Greening Tree Species for Urban Road in Xiamen. *Chin. Landsc. Archit.* **2018**, *34*, 83–87.
35. Yang, M.; Défossez, P.; Danjon, F.; Fourcaud, T. Analyzing key factors of roots and soil contributing to tree anchorage of Pinus specie. *Trees-Struct. Funct.* **2018**, *32*, 703–712. [CrossRef]
36. Shang, X.H.; Zhang, P.J.; Xie, Y.J.; Luo, G.Z.; Li, C.; Wu, Z.H. Wind resistance correlated to growth and wood properties of 50 *Eucalyptus camaldulensis* provenance families. *J. Zhejiang A F Univ.* **2017**, *34*, 1029–1037. [CrossRef]
37. James, K.; Haritos, N.; Ades, P. Mechanical Stability of Trees under Dynamic Loads. *Am. J. Bot.* **2006**, *93*, 1522–1530. [CrossRef] [PubMed]
38. James, K.; Hallam, C.; Spencer, C. Tree Stability in Winds: Measurements of Root Plate tilt. *Biosyst. Eng.* **2013**, *115*, 324–331. [CrossRef]