A LANDSCAPE MODELING RESEARCH: COLUMNAR VISUAL FORM (*CUPRESSUS SEMPERVIENS*) AND WIND SPEED REDUCTION

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ABSTRACT

Natural windbreaks, such as rows of trees with various distances among them, have been utilized to slow wind speed. The current study numerically investigated the effect of natural windbreaks, i.e., trees with columnar (Cupressus sempervirens sp.) canopy shape, on wind speed reduction in urban open spaces. Computational Fluid Dynamics (CFD) was used to simulate airflow through the trees as 3-D forms. The effects of various criteria, such as the number of tree rows, gaps between trees, trees arrangement patterns, and height levels, were examined on wind speed reduction. The association between factors affecting wind velocity was also studied using Spearman's rank correlation. According to the results, the best wind speed reduction was detected for the heights above 5 m with a 0.5 m gap distance among tree canopy. A rectangular two-row arrangement of trees was observed as the most effective pattern in decreasing wind speed compared with the other (one-raw and triangular two-raw) arrangements. The correlation results revealed a direct significant association between distance from windbreak and wind speed reduction (r = 0.581, α= 0.001). It is recommended to use a rectangular planting pattern with a 0.5 m distance between tree canopies in the columnar canopy.

Keywords: *Natural windbreakers, Wind speed reduction, Tree canopy shape, CFD*

1. INTRODUCTION

Urban areas are affected by severe winds in each geographic region, hence, winds are one of the most destructive factors that impact urban activities. In urban environments, the microclimate and personal well-being are influenced by wind conditions. Furthermore, humans use shelterbelts as techniques to improve the climatic condition, and earlier studies were conducted to find the best method to logically reduce strong wind effects (Erich and Plate, 1971). In this situation, therefore, using plants with adequate strength and aesthetical values is required to withstand undesirable winds. Trees as natural elements are able to save the life and micro-environment of humans. Since shelterbelts are capable of reducing wind annoyance, they have been used throughout the world (Basnet, 2015). Lately, trees have been used as windbreak trees to moderate environmental matters such as wind velocity. The tree plantation pattern is one of the most important factors that should be considered in studies. The first step is to identify if each pattern will be a mono-species plantation, or if it will be planted in two or more species in different arrangements. Therefore, the significant function of windbreaks is to inhibit the wind flow and shift flow patterns on the windward and leeward of the obstacle (Brandle, 2009). Man-made barriers are prepared using substances such as metal, concrete, wood, stone, plastic, sod, or vegetation (Ver Cauteren et al., 2006). Artificial barriers are often made of stiff materials and are often thin with built-in 2-D structures (Khalil, 2008), however, plants are 3-D structures, and the formation of windbreaks is by planting one row or more of trees and shrubs (Cornelis & Gabriels, 2005). Numerical simulations, field, and wind tunnel tests during windy daytime situations indicate that medium density barriers notably slow wind speeds behind and within the barrier, causing turbulence within the shelterbelt and generating a quiet zone (Rajewski, 2007).

In recent decades, shelterbelts, greenbelts, or windbreaks benefit agricultural settings in a wide variety of applications: wind speed reduction can protect structures, such as houses, outbuildings, roads, etc. from noises (Slusher and Wallace, 1997), and can prevent air pollutants from diffusion (Heisler and Dewalle, 1988). Windbreaks, such as trees and shrubs, have also been identified as protection providers for crops, animals, people, and their property in urban areas from the effects of a tough climate (Li et al., 2007). In this case, the main benefit of windbreaks is wind speed reduction, which leads to various benefits such as lower heating expenses at home or preparing human welfare conditions (Zhang et al., 2015).

The most efficient factors of aerodynamic features depend on density, the height of trees, width, shape, porosity, and tree arrangements (row number and row space are more important wind obstacle features that have attracted many researchers (Bitog et al., 2011), as well as the main external factors such as wind velocity and wind direction. Previous studies (Bitog et al., 2009; Cornelis & Gabriels, 2005) show that the porous barriers have an important effect on the efficiency of shelterbelts. However, there is no actual measurement method to define the porosity of trees. Shelterbelt and windbreak flows are the subject of ongoing studies in field experiments, wind tunnel experiments, and numerical modeling. Computer simulations have been executed to study the effect of natural and artificial windbreaks to survey factors related to the airflow mechanism around obstacles. Dong et al. (2008) studied the natural windbreaks experimentally in the wind tunnel. Bitog et al. studied the effect of black pine trees as shelterbelts using numerical simulation (Bitog et al., 2009). Other numerical simulations (e.g., Rosenfeld et al. 2010) have been used to investigate the wind flow characteristics around natural and artificial windbreaks. Hipsey et al. (2004) proposed a combined field experiment and numerical simulation. Furthermore, Bitog et al. (2012) used experimental results in numerical simulations in Korea to design effective windbreak systems to control dust. Rosenfeld et al. (2010) investigated the impact and value of 3-D airflow patterns across windbreak trees consisting of cypress trees. These studies demonstrate that CFD is an applicable numerical technique to investigate flow characteristics such as wind speed. Previous research also investigated the mean speed and turbulence stress downward of a porous fence (Castro and Garo (1998). Wilson and Yee (2003) expanded a numerical archetype to simulate wind flow around single and multi-array windbreaks. There are also two valuable reviews by Caborn (1957) providing the common understanding of a windbreak classification and the microclimatic factors affected by windbreaks. Heisler and Dewalle (1988) presented a review on the effect of windbreak structures on wind flow and some secondary effects related to wind speed reduction.

In sum, studies conducted by Li and Sherman (2015), Bitog et al. (2012), Rosenfeld et al. (2010), Gromke and Ruck (2008), and Santiago et al. (2007) are important investigations that have applied CFD for the analysis of wind flows over an environment or an extent sheltered by windbreaks. Several observations and wind tunnel studies illustrate that windbreaks provide the most effective wind speed reduction in the leeward region and optimize temperature and humidity for agricultural activities (Brandle et al. 2004). Windbreaks alter wind flow patterns and protect extended areas behind the windbreaks. Therefore, structural features of windbreaks can influence the total extent of the preserved area and can reduce wind speed and improve microclimatic conditions (Zhou et al., 2005). Consequently, serious problems caused by high-speed winds around the world have persuaded researchers since the 1930 and 1940s to discover appropriate planting patterns for windbreaks as it is a critical requirement to adequately reduce wind speed in landscape architecture.

The effects of windbreaks on reducing wind speed were evaluated using different planting patterns in urban areas to reduce wind speed on urban open spaces. Planting patterns comprise the fence porosity, the number of tree rows, gap distance between trees, and crown shape, which are the main factors in controlling wind speed. In this study, Cupressus sempervirens (a sample of the columnar shape) was chosen as a case study using trees with columnar crown shapes. The wind speed reduction was evaluated at different distances along the windward and leeward directions from the windbreak. To the best of the authors' knowledge, there is no study investigating the windbreak performance based on crown-shaped trees. Although the current study is conducted for a specific crown shape (columnar form), the results attained in this study can be used to compare the capability of trees with other crown shapes with decreased wind speed in future studies. The results achieved will be employed in the design of green belts in urban areas as an effective windbreak system.

2. MATERIALS AND METHODS

Computational fluid dynamics (CFD) has been broadly applied as a dominant implement for simulating certain natural phenomena. Manufacturing test setups are expensive and time-consuming for many studies in the natural environment. However, using numerical techniques, such as CFD methods, makes such studies feasible and can reduce costs. In this study, CFD was applied to observe the effect of planting patterns on decreasing wind power. The ANSYS Workbench R. 15.0 Commercial code was also used in all the conducted procedures. Through using the numerical technique, computer simulations were performed to simulate the environmental conditions in a real wind tunnel to validate the results with empirical results from earlier studies. The wind tunnel can be cited as a research domain, which has been used in studies to investigate the impact of airflow around a buffer. In computational modeling of turbulent flows, a common goal is to achieve a model that can predict quantities of interest, such as fluid velocity, for use in engineering designs. Dividing the domain into a set of non-overlapping attached rectilinear cells and applying the boundary conditions for boundary nodes result in a linear equation that solves algebraic equations, velocity, pressure, and temperature in the computational domain. Furthermore, numerical methods were applied to resolve the linearized potential equations. CFD simulation was used to solve momentum and continuity equations. The continuity equations are the basis for certain transmission equations such as the Reynolds-averaged-Navier-Stokes (RNAS) equation. The RNG k- model is vastly used to simulate the wind flow turbulence in wind tunnels. The SST k– model was selected because of its ability to simulate wind flow near small grooves with high precision. The calculation was done using the RNG k–3 turbulence model, which is very popular for general CFD simulations with reasonable accuracy (Launder and Spalding, 1972). However, k- is a rather authentic model to employ in this research based on Guo and Maghirang (2012). The importance and efficiency of the Fluent commercial code for this category of numerical simulations have been argued by other researchers (Bitog et al., 2012, Rosenfeld et al, 2010; Lee and Lim, 2001; Rosenfeld et al, 2010; Rajewski, 2007; Wilson & Yee, 2003). Equations for continuity and RANS are presented as follows:

$$\frac{\partial v_i}{\partial x_i} = 0 \quad (1)$$

$$\bar{\mu}_j \frac{\partial \mu_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \upsilon \frac{\partial^2 \bar{\mu}_i}{x_j^2} - \frac{\partial}{\partial x_j}\left(\mu_i' \mu_j'\right) \quad (2)$$

where p, μ, v and p are air density (kg.m-3), air viscosity (N.s.m-2), velocity (ms-1), and pressure (Pa), respectively. The current research utilizes numerical methods to augment the accuracy and accelerate performing simulations such as those for turbulent flows. The primary objective of this study is to assess the efficiency of trees with the columnar crown shape in wind speed reduction. In this survey, C. *sempervirens* has a columnar shape, and the geometry of trees was created as a 3-D model that was made by the design modeler environment of ANSYS Workbench. The 3-D model was designed assuming the general shape and dimension of C. *sempervirens*. The visual perception of the tree geometry was chosen based on Muderrisoglu et al. (2006). Trees mature in different sizes and dimensions in each geographic region. The average dimensions for C. s*empervirens* wee considered for the trees growing in Iran, which shows compatibility with real case studies existing in the country. The research is conducted to simulate the windbreak trees in the natural environment. The most physical characteristics of tree species are canopy width, and height and those for C. *sempervirens* were about 2 m and 14 m, respectively. The porosity for C. *sempervirens* was estimated at 15% (85% density) at the maximum growth level. The numerical simulation is capable of defining the effectiveness of the gap distance between trees, the number of tree rows, and the arrangement in decreasing wind velocity. The quantities of wind speed reduction were investigated at varying heights from the ground (h=1, 2, 3, 4, and 5 meters). Therefore, the Spearman rank correlation was considered to find relationships between wind speed reduction factors (Edwards, 1976; Spearman, 1904). The Spearman rank correlation estimates the extent to which two variables are related to each other.

2.1 The computational domain and numerical considerations

The total length of the computational domain was 140 m, and the windward and leeward lengths were designed at 27.5 and 112.5 m, respectively. The total height of the domain was also designed at 5H or 70 m, with the H referring to the tree height (14 m). In simulation studies, the 5H has been recommended as the minimum height of the computational domain (Tominaga et al. 2008); Blocken et al. 2007); Franke et al. 2004).

The width of the simulated wind tunnel domain for C. *sempervirens* was taken at 6.0, 6.75, and 7.5 m depending on the gap distance between trees, namely 0.50, 0.75, and 1.00 m, respectively (Table 1). Based on the width of the tree crown, these dimensions are also considered different. The minimum and maximum sizes of the smallest grid cells were about 0.2 and 1.0 m, respectively. The small size was needed to resolve the flow around upwind and downwind faces.

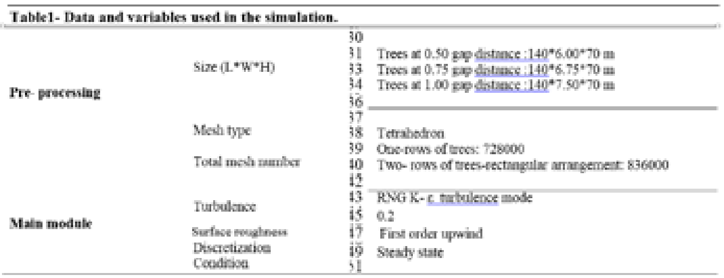


Table1- Data and variables used in the simulation.

Pre- processing	Size (L*W*H)	Trees at 0.50 gap distance :140*6.00*70 m Trees at 0.75 gap distance :140*6.75*70 m Trees at 1.00 gap distance :140*7.50*70 m
	Mesh type	Tetrahedron
	Total mesh number	One-rows of trees: 728000 Two- rows of trees-rectangular arrangement: 836000
Main module	Turbulence	RNG K- ε turbulence mode
	Surface roughness	0.2
	Discretization	First order upwind
	Condition	Steady state

Both sides of the computational domain are symmetrical while the upper and lower sides of the section are considered as surface walls. One side of the computational domain has the velocity inlet boundary condition, while the opposite side of the inlet boundary has the pressure outlet boundary condition. To know the usage of the inertial resistance in the simulation, the tree canopy volume was considered as fluid and the porous zone was activated.

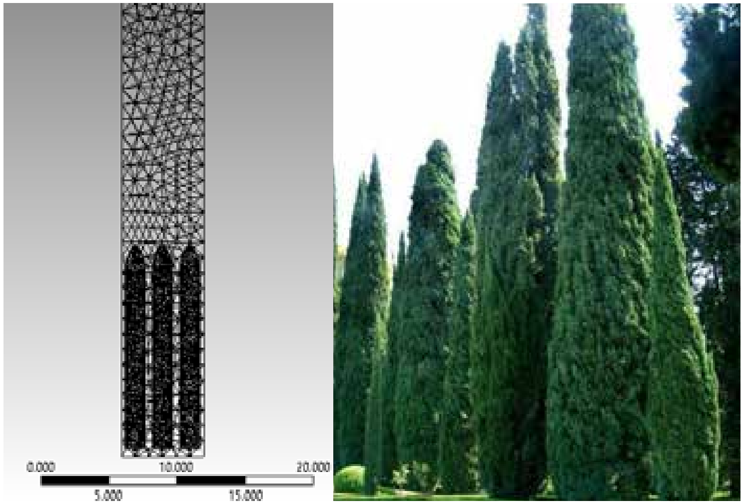


Figure 1: *The columnar crown shape (left); Cupresus sempervirens (right)*

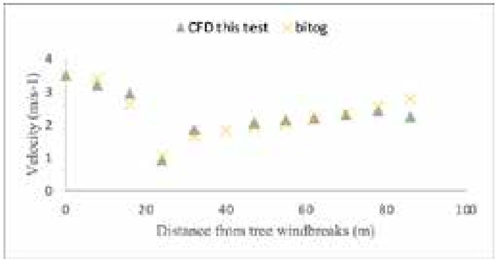
Rosenfeld et al. (2010) considered several densities for cypress. In this study, the porosity value for C. sempervirens was considered at 15% based on different growth conditions, especially in Iran (Figure 1, shows the grid model of the tree in CFD (left) and the photo of C. sempervirens (right) as a tree with a high density and low porous natural windbreak.

3. RESULTS AND DISCUSSION

3.1. CFD simulations

3.1.1. Validation of the simulations based on previous studies

The main aim of CFD simulations is to assess the capability of numerical simulations to evaluate the airflow around obstacles, which shows the significance of validating the CFD outcomes with previously accepted results. In this study, the results were verified by comparing the achieved results with those presented by Bitog et al. (2012), where black pine trees were used to control dust pollution in the coastal areas in Korea. Therefore, a standard using black pine trees was developed to compare the results with their work before using C. sempervirens trees as the elements applied for the current study. Figure 2 illustrates the model validation for black pine trees in one row with a 0.50 gap distance between them. Accordingly, the results display acceptable agreement with the corresponding results reported by Bitog et al. (2012).



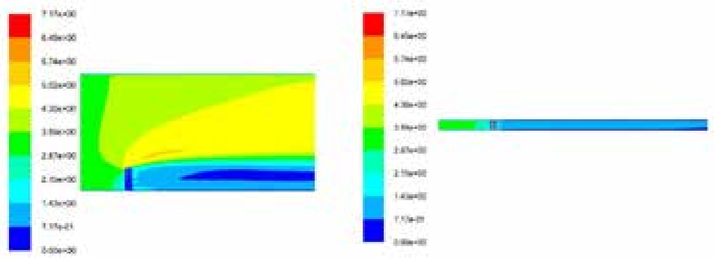
Bitog et al (2012)	this research results
2.85	7.71
24.5	16.0
70.5	73.5
52.8	46.8
46.5	41.4
45.1	57.4
41.7	37.4
37.7	34.0
32.8	35.7
27.4	31.1
20.5	35.0

Figure 2*: Comparison of the results with the simulation results obtained by Bitog et al. (2012) for Black pine trees*

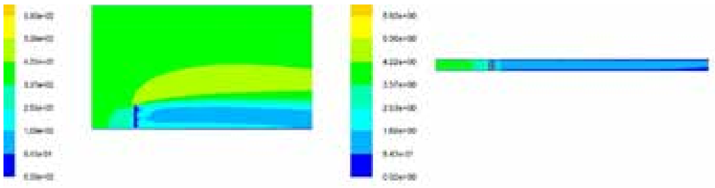
In previous studies, all the components of the current model, for instance, the porous model of the canopy, the extent of the computational model, and the turbulence model were investigated and validated. (Katul et al. 2004; Sogachev and Panferov 2006; Bourdin and Wilson 2008). Santiago et al. (2007) tested the accuracy and applicability of the Fluent CFD package.

3.1.2. The airflow in the shelterbelts region behind natural windbreaks

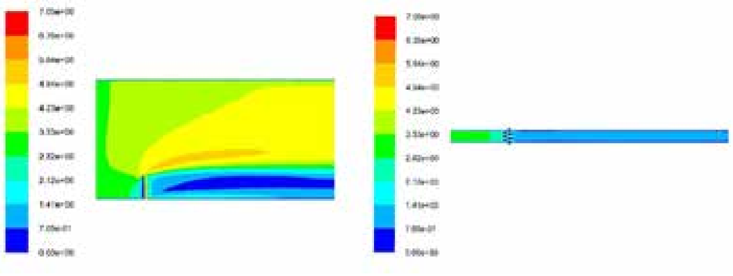
The velocity distribution in the computational domain for various arrangements (Fig. 3) shows the effect of 0.50 m gap distance between trees of a row. The wind initial speed is 3.5 m s-1. As can be seen, the spaces between trees in a row act as a funnel, and the wind is trapped between the gaps. Besides, the maximum efficiency at the wind speed reduction is on the leeward side of a barrier. One appropriate scheme is to modify the effect of tree windbreak in wind speed reduction by applying a rectangular two-row planting arrangement. However, such an arrangement is more efficient in decreasing wind speed at the extents near to the windbreak than the triangular arrangement. It is due to the creation of high-velocity regions exactly after the windbreak for the triangular arrangement, which deactivates the windbreak effect.



A: 1 row, 0.50m gap



B: Rectangular two- row, 0.50m gap



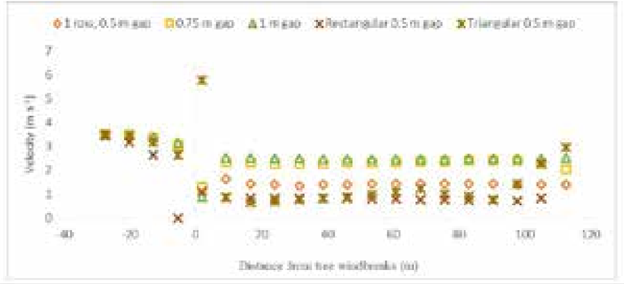
C: Triangular two-row, 0.50m gap

Figure 3: *Velocity distribution around tree windbreak): a. side view and b. top view at 4m height*

Figure 4 demonstrates wind velocity for different arrays at different spacing and different heights from the surface. As can be seen, velocity undergoes a sudden decrease after the windbreak because of the relative stagnation condition created behind the windbreak. Velocity is retrieved by increasing distance from the trees while its magnitudes at different distances are not as high as the initial wind speed. For 1 row, rectangular 2-row, and triangular 2-row arrangements, 0.5 m gap displays the most effective influence on velocity reduction. For 2-row arrangements, only the results of the 0.5 m gap case study are brought for the sake of abbreviation. The rectangular arrangement shows better results at closer and further regions, which can be attributed to a columnar crown shape of trees. On the other hand, the 5-m height shows the best velocity decrease among different heights from the ground, which is due to the canopy spread at that height.

A. h=3m

B. h=4 m



C. h=5 m

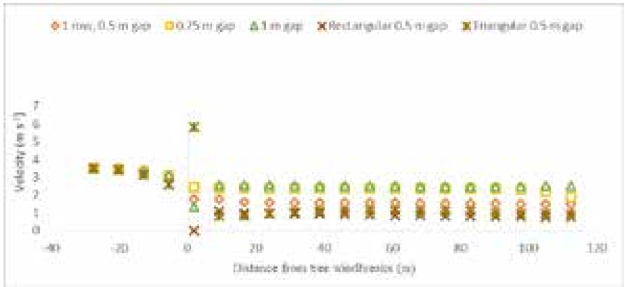


***Figure 4**:* *Wind velocity for different arrangements at different distances and different heights (3, 4, and 5m) from the ground*

It could be mentioned that windbreaks enhance mean momentum and increase turbulence above the shelterbelt top and in the leeward area. Conversely, shelterbelts slow mean momentum and reduce turbulence near the surface in their leeward areas (Zhou et al., 2005).

3.1.3 The effects of gap distance between trees, number of rows, and tree arrangement on speed reduction

- Single-row tree windbreak

First, analyzing a one-row tree planting pattern with a 0.5 m gap distance between trees is proven to be more effective in reducing wind speed. For instance, the percentages of wind velocity decline of one-row tree planting with 0.50, 0.75, and 1.00 m gap distances are 59.0, 33.9, and 28.1%, respectively, at the 5-m height from the surface at the distance of 16 m behind the windbreak. Moreover, the reduction percentage values for 4-m height from the surface with 0.50, 0.75, and 1.00 m gaps are 54.0, 31.5, and 26.5%, respectively, at the same distance (Table 2). Furthermore, the wind speed is shown to reduce gradually on the windward side. The simulation results clearly showed the effectiveness of tree windbreaks in wind speed reduction, especially adjacent to the leeward. The results indicate that a 0.5 m gap distance between trees in the one-row arrangement provides shielding of a wider zone behind the windbreak trees from unfavorable effects of wind. In addition, the reduction is 59.2 and 59.5%, respectively, for the distances of 46 and 112 m from the windbreaks with a 0.50 m gap between trees at 5-m height. The corresponding reduction percentages are 55.1 and 57.4% at the same distances for a 4 m height from the surface. For a 5 m height from the ground, the 0.5 m gap shows the highest wind speed reduction. The average wind speed at leeward regions of the windbreaks with different gaps of 0.50, 0.75, and 1.00 m are respectively 1.42, 2.26, and 2.39 m s-1, at the height of 5 m above the ground (Table 6). Accordingly, wind velocity decrease is maximum in the area behind the windbreaks for a 0.50 m gap in comparison with 0.75 m and 1 m gaps.

- Rectangular two-rows of tree windbreaks

In terms of rectangular two-row tree windbreaks at a height of 5 m, reductions for 0.50, 0.75, and 1 m gaps at a distance of 16 m are 74.9, 45.9, and 42.2%, respectively. At the distances of 46 m, the corresponding values are 76.3, 53.7, and 44.9%, respectively. The results show that the greatest wind speed decrease occurs at a 0.50 m gap for both adjacent and far distances in comparison to 0.75 and 1 m gap distances. The percentages of reduction are 74.9, 76.9, and 79.3%, respectively, for 5 m height from the surface with a 0.5 m gap at 16, 61, and 112 m distances (Table 6). Besides, the wind speed reductions are 72.0, 74.5, and 78.6%, respectively, at a height of 4 m from the ground for the 0.5 m gap at distances of 16, 61, and 112 m. On the leeward side of the rectangular two-row arrangement, the average wind speed values are 1.05, 0.99, 0.91, 0.83, and 0.82 m s-1, respectively, for 1, 2, 3, 4, and 5 m heights from the surface with a 0.50 m gap (Tables 2, 3, 4, 5, & 6). This is similar to the corresponding values of the single-row arrangement.

Table 2: *Percentage decrease of wind velocity measured at 1 m height*

Number of rows/ arrangement	Gap distance (m)	Distance from the trees (m)										Average speed	
		-20	-12	16	31	46	61	75	90	97	112	Wind ward	Lee ward
One row	0.50	1.54	7.39	38.0	41.7	45.0	47.7	49.6	51.7	52.5	54.1	3.25	1.81
	0.75	0.95	4.80	25.9	28.6	30.0	31.2	32.3	34.2	35.5	36.8	3.34	2.40
	1.00	1.01	4.28	18.7	22.9	25.3	26.6	27.7	28.3	28.5	28.4	3.19	2.58
Rectangular Two- rows	0.50	2.49	11.5	57.6	63.4	66.9	69.5	71.7	73.9	74.8	75.9	3.13	1.05
	0.75	2.07	9.26	54.9	58.1	58.9	59.7	60.2	60.2	60.3	61.0	3.19	1.36
	1.00	1.43	6.25	39.6	42.7	44.5	45.6	46.2	46.7	46.7	45.1	3.29	1.81
Triangular Two- rows	0.50	2.53	10.9	31.9	43.1	50.0	54.1	58.0	62.4	64.5	66.5	3.14	1.92
	0.75	1.89	8.16	32.6	40.4	45.3	48.8	51.6	53.7	54.5	56.2	3.23	2.05
	1.00	1.45	6.34	29.7	36.1	40.4	42.9	44.7	45.8	46.3	47.3	3.29	2.20

Table 3: *Percentage decrease of wind velocity measured at 2 m height*

Number of rows/ arrangement	Gap distance (m)	Distance from the trees (H: tree height)										Average speed	
		-20m	-12m	16m	31m	46m	61m	75m	90m	97m	112m	Wind ward	Lee ward
One row	0.50	1.82	7.99	28.3	35.9	41.4	45.3	48.1	50.6	51.6	53.2	3.24	2.02
	0.75	0.78	4.23	26.3	28.8	30.3	31.1	31.8	32.7	33.4	34.5	3.35	2.41
	1.00	0.71	3.69	20.8	23.9	25.5	26.6	27.4	27.8	28.0	27.6	3.37	2.53
Rectangular Two- rows	0.50	2.19	10.3	61.8	65.7	68.4	70.6	72.6	74.4	75.3	77.2	3.15	0.99
	0.75	1.79	8.51	49.0	55.2	57.2	58.2	58.7	58.9	59.1	59.6	3.21	1.45
	1.00	1.14	5.55	36.6	41.8	43.9	45.0	45.7	46.0	46.0	44.2	3.31	1.86
Triangular Two- rows	0.50	2.22	10.1	48.8	51.3	54.4	57.6	60.4	64.0	65.9	67.7	3.15	1.73
	0.75	1.58	7.63	44.3	45.4	48.8	50.9	52.9	54.6	55.2	56.6	3.24	1.91
	1.00	1.18	5.69	34.5	38.3	41.6	43.6	44.9	45.9	46.2	46.9	3.30	2.13

Table 4: *Percentage decrease of wind velocity measured at 3 m height*

Number of rows/ arrangement	Gap distance (m)	Distance from the trees (H: tree height)										Average speed	
		-20m	-12m	16m	31m	46m	61m	75m	90m	97m	112m	Wind ward	Lee ward
One row	0.50	1.52	7.16	47.6	48.6	49.3	51.0	52.2	53.9	54.3	55.4	3.25	1.71
	0.75	0.79	4.06	28.6	30.4	31.2	31.6	32.1	32.3	32.5	33.1	3.35	2.38
	1.00	0.67	3.50	23.9	25.6	26.7	27.3	27.7	27.9	28.0	27.4	3.37	2.45
Rectangular Two- rows	0.50	2.16	9.98	67.1	69.0	70.8	72.3	73.8	75.3	76.1	77.7	3.16	0.91
	0.75	1.77	8.21	46.2	53.2	55.7	56.9	57.5	57.9	58.1	58.7	3.21	1.49
	1.00	1.11	5.38	38.3	42.1	44.0	45.0	45.5	45.8	45.7	43.8	3.31	1.85
Triangular Two- rows	0.50	2.15	9.82	64.7	60.8	60.2	62.3	63.9	66.9	68.0	69.0	3.16	1.52
	0.75	1.55	7.33	53.1	51.7	53.0	54.3	55.1	56.3	56.9	57.8	3.25	1.77
	1.00	1.14	5.51	39.0	41.5	43.4	44.9	45.8	46.5	46.8	47.2	3.31	2.07

Table 5: *Percentage decrease of wind velocity measured at 4 m height*

Number of rows/ arrangement	Gap distance (m)	Distance from the trees (H: tree height)										Average speed	
		-20m	-12 m	16m	31m	46m	61m	75m	90m	97m	112m	Wind ward	Lee ward
One row	0.50	1.47	6.89	54.0	54.8	54.6	55.1	55.7	56.4	56.7	57.4	3.25	1.58
	0.75	0.77	3.98	31.5	32.3	32.5	32.2	31.9	32.1	32.3	32.1	3.35	2.33
	1.00	0.66	3.38	26.5	27.5	28.1	28.2	28.4	28.5	28.3	27.4	3.37	2.45
Rectangular Two- rows	0.50	2.09	9.55	72.0	72.9	73.5	74.5	75.6	76.7	77.3	78.6	3.17	0.83
	0.75	1.70	7.96	45.4	51.8	54.5	55.9	56.6	56.9	57.1	57.8	3.22	1.52
	1.00	1.09	5.18	41.1	43.1	44.4	45.2	45.6	45.7	45.5	43.5	3.31	1.83
Triangular Two- rows	0.50	2.06	9.41	76.5	69.4	67.9	67.5	68.0	70.0	71.4	72.2	3.17	1.33
	0.75	1.51	7.07	58.5	58.2	57.5	57.9	58.1	58.8	59.0	59.8	3.25	1.64
	1.00	1.10	5.28	42.3	44.3	45.5	46.5	47.0	47.5	47.5	47.7	3.31	2.03

Table 6: *Percentage decrease of wind velocity measured at 5 m height*

Number of rows/ arrangement	Gap distance (m)	Distance from the trees (H: tree height)										Average speed	
		-20m	-12m	16m	31m	46m	61m	75m	90m	97m	112m	Wind ward	Lee ward
One row	0.50	1.39	6.56	59.0	61.1	59.6	59.2	59.0	59.2	59.4	59.5	3.26	1.42
	0.75	0.73	3.85	33.9	34.1	33.8	33.0	31.7	32.7	32.4	31.5	3.35	2.26
	1.00	0.64	3.26	28.1	29.0	29.2	29.2	29.1	29.0	28.7	27.5	3.37	2.39
Rectangular Two- rows	0.50	1.98	9.07	74.9	76.2	76.3	76.9	77.7	78.3	78.8	79.3	3.18	0.82
	0.75	1.62	7.55	45.9	51.0	53.7	55.0	55.7	56.0	56.1	57.0	3.23	1.54
	1.00	1.05	4.92	42.2	43.8	44.9	45.5	45.7	45.7	45.4	43.1	3.32	1.82
Triangular Two- rows	0.50	1.95	8.96	81.4	77.8	74.8	72.8	72.7	73.8	75.2	75.4	3.18	1.20
	0.75	1.42	6.72	61.3	62.5	62.0	61.5	61.7	61.6	61.5	61.5	3.26	1.54
	1.00	1.07	5.05	44.4	46.6	47.6	48.0	48.3	48.4	48.3	48.2	3.31	1.96

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- Triangular two-rows tree windbreaks

The wind speed reductions for triangular two-row trees with three different gap distances (0.50, 0.750, and 1.00 m) are 81.4, 61.3, and 44.4%, respectively, at a 5-m height from the surface at a 16-m distance (Table 6). The velocity increases in the case of the flow between the trees, when the flow moves through the gap between the canopies, partly because of the narrowing of the cross-section, but mostly because of the surplus flow refused by the canopy. The values of wind velocity diminishing at 61 and 112 m are 72.8 and 74.5%, respectively, with a 0.5 m gap distance. In addition, wind velocity decrease percentages are 76.5, 67.9, and 72.2%, respectively, at 16, 46, and 112-m distances at a 4-m height from the surface (Table 5). The maximum diversity is gained in the middle of the canopy. At greater heights, the diversity decreases with the reduction of the canopy diameter, narrowing the amount of the locally decreased velocity.

***Table** 7: Correlations (r) between wind speed and effective factors (Spearman's Rho result)*

Number	Factors	Wind speed	Sig. (2-tailed)
1	Row	r = 0.316**	0.001
2	Gap	r = 0.457**	0.001
3	Distance	r = 0.581**	0.001

** p < 0.01, * P < 0.05

As shown in Table 7, wind speed reduction behind the windbreak is mostly affected by factors such as the number of rows, gap distances, and lateral distances. A significant positive correlation is observed between wind speed decrease and the number of rows (r = 0.316**), which is considered a low correlation, followed by a correlation between the gap and wind speed (r =

0.457**) as a medium correlation. Finally, the distance is highly correlated with wind velocity at r = 0.581**, which is considered as a relatively strong correlation, showing a significant increase in the wind velocity with rising the distance from windbreaks. In a negative or indirect relationship, an increase in the gap distance between trees enhanced wind speed. The increased velocity value (Tables 2, 3, and 4) is due to the gaps between the windbreak trees acting as tunnels that concentrate the wind flow. Therefore, it is expected that the effectiveness of the windbreak decreases with increasing the gap distance.

4. DISCUSSION

According to the results for the single-row tree windbreak, Tables 2, 3, and 4 clarify that the wind velocity decrease is enhanced by raising the height from the surface at 1, 2, and 3-m heights from the ground. The velocity increases near the ground leeward of the stem, as was also remarked by Gross (1987) in relation to a single tree with a solid stem. Wu et al. (2012) illustrated that the effect of row numbers decreased significantly at a rather far lateral distance from the barrier. The advantage of the current model is its ability to study 3-D flow patterns obtained by the internal shape of the windbreak and, consequently, this aspect has been highlighted in this paper. In the gap between adjacent canopies, the wind velocity is only marginally speeded up, generating a lateral alternating flow of decreased wind velocity leeward of the canopies and larger velocity in the gap between them. Therefore, it shows an inverse relationship between the gap distance increase and wind speed reduction values. The key finding of Dupont and Brunet (2008) illustrates that the development of flow at these transitions is heavily influenced by the shape of the canopy edge and the distribution of the plant canopy with height.

Regarding rectangular two-row tree windbreaks, a windbreak with a rectangular two-row arrangement of trees is capable of enhancing the resistance and ameliorating the effectiveness. The gap distance between the tree rows is the main parameter that needs to be considered. Three different gap distances (0.50, 0.75, and 1 m) were measured between the rows. Comparing the results of velocity reduction values at different heights from the surface illustrates that the maximum wind speed reduction is seen at a 5-m height with 0.50 m gaps.

In terms of triangular two-row tree windbreaks, comparing the results achieved from using the three mentioned tree planting arrangements reveals that the rectangular two-row pattern is more effective for reducing wind speed than the other two schemes. The average of wind velocity is 1.33 m/s-1 at a 0.5 m gap distance at a 5-m height for the triangular two-row planting arrangement while the reduction values are 0.83 and 1.58 m/s-1 for rectangular two-row and single-row planting patterns, respectively.

These simulation results are in better agreement with the overall conclusion defined above. It is clear that a rectangular shape has a significant impact on wind velocity decrease. Moreover, the two-row planting with a rectangular pattern provides the highest effective resistance against wind. Designing an appropriate windbreak is an efficient method to control severe winds. Trees with different crown shapes have different effects on wind speed reduction. Our investigations are conducted on C. sempervirens as a typical tree with the columnar crown shape that is planted in many regions throughout the world. Further studies may concern surveys about trees with other crown shapes.

In this study, the results illustrated that the distance between the trees, arrangements, and the number of tree rows can be considered important factors. These results are consistent with those of prior research. A simulation study by Bitog et al (2012) showed that the effectiveness of windbreak trees could be decreased by raising the distance between the trees, which is consistent with the results of the current investigation. The percentage decline of wind speed because of the windbreak trees, as influenced by rows of trees, gap distances, and different arrangements at different heights from the ground are presented in Tables 2, 3, 4, 5, and 6. Results revealed that a 5-m height from the surface had the highest effect on the wind speed reduction. The maximum wind speed reduction was observed at closer regions behind the windbreaks, while wind speed was retrieved at further regions. Therefore, the percentage of wind speed reduction is affected by the gap distance between trees and their arrangements.

5. CONCLUSION

The current study simulated numerically the airflow among arrangements of Cupressus trees in a 3-D wind tunnel model. It also investigated the effects of different parameters, such as the gap distance between trees in a row, the number of tree rows, and the planting arrangement, to evaluate the ability of the natural windbreaks to reduce wind speed at different heights from the surface and different distances behind the windbreak. The wind speed decrease and the extent of windbreak effectiveness depend on the density of tree canopies. Major results are briefly described in the following:

At 1, 2, 3, 4, and 5 m heights from the surface, a 0.5 m gap shows the best results for single-row, rectangular, and triangular two-row arrangements. For the rectangular two-row arrangement, comparing rectangular and triangular results shows that the former is better than the latter for wind speed reduction at all the heights from the surface. This is due to the diversity between the minimal and maximal wind velocities at the bottom of the canopy, which is small because of the adjacency between the canopies. This diversity is enlarged with height with widening the gap. As the maximum diversity is gained in the middle of the canopy, the rectangular two-row arrangement demonstrates the best and most effective performance in reducing wind speed at large extents of the investigated area behind the windbreak. The findings of this study are applicable in urban environments, particularly in designing green belts because the reduction of wind speed on the top of the ground is more important than that on the ground surface. However, a species with a lower height of the crown is recommended to be tested to reduce wind speed in farmlands and gardens.

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