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CFD Simulation of Airflow Distribution inside Coconut Tree Canopies with Different Cropping Patterns

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Abstract

Coconut trees around coastal regions are particularly vulnerable to cyclones, which can cause severe damage due to high wind speed and turbulent airflow. The agricultural sector plays a critical role in meeting human needs. A large number of people make their living directly from agriculture. Slender trees like bananas, coconuts, palms, etc., are getting affected and also impacted by natural disasters like cyclones and storm winds, so in the current scenario, it's crucial to know how wind flows around such trees. This paper presents a study using Computational Fluid Dynamics (CFD) to simulate airflow distribution within a coconut tree orchard, focusing on two distinct planting patterns — The first case study is the arrangement of trees in a uniform pattern and the second case study is a staggered arrangement. The CFD simulations provide insights into the study of the planting geometry, wind stress on the trees and identify the orchard layouts that can reduce cyclone-induced damages. When the wind blows during a cyclone, its natural frequency shouldn't match the shedding frequency of the vertices striking the body; if they do, there is a chance for failure. The present study contributes to developing more resilient coconut tree orchards in cyclone-prone coastal areas. Also, it offers a practical guideline for enhancing agricultural sustainability by minimizing the impact of extreme weather events.

Keywords: Airflow Distribution Inside Canopies, CFD Application in Agriculture, Cyclone Effect in Agriculture, Wind forces on trees.

Introduction

In the last 20 years, CFD has been used in the field of agriculture to make numerous solutions for various problems such as fluid flow, including air and water, across multiple farming environments, agricultural structures like greenhouses, orchards, and irrigation systems, gaseous pollutants in chicken houses, which helps with designing more effective layouts for better pollination, pest control, and pesticide application. Using CFD to measure fluid behavior, which is difficult to measure experimentally, can help agricultural managers make better decisions by offering detailed insights. This results in increased crop yield, resource efficiency, and sustainability of general farming practices.

CFD studies were done in comparing the wind patterns around palm and coconut trees (1). Further many research studies were done to study the wind flow on two distinct cross-sectional profiles near the tree bark, and those behaviors were examined. Moreover, some research studies describes that the CFD is an efficient tool and has drawn extensive attention from scholars cond ucting research within the biological and agricultural engineering fields (2). The steady and unsteady wind flow around a 3D Rhizophora mangrove tree model and examined the velocity profile, pressure distribution, drag coefficient, and force were examined (3). Moreover, Rhizophora mangroves can protect the coast by reducing wind velocity. The uniformity and precision of pesticide spray flows and deposition into canopies, as well as the off-target transport of spray droplets released from air-assisted sprayers in apple orchards, by accurately simulating pesticide droplet deposition coverage (4). A multirotor Unmanned Aerial Vehicle (UAV) sprayer to numerically simulate the distribution of downwash airflow inside tree canopies of an apple orchard (5). A physics-based model to simulate the large, dynamic deformation of trees in the presence of strong winds and also considered sma ll deformations that failed to properly account for wind-induced damage (6).

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An integrated CFD model (7) were done to simulate air velocity distributions within and outside tree canopies sprayed by an air-assisted pesticide sprayer and simulated maximum air velocity and airflow pressure within the canopies with mean RMS errors. The experiments were intended to allow for a study of the coherent gust structures in the flow and a quantitative evaluation of the wind stability of the specific forest arrangements (8). A set of 1:75-scale wind tunnel experiments examining wind flow over and through three distinct forest models and the resulting wind loading on individual model trees. The impact of wind loading on two various three-dimensional tree models through numerical simulation with application to urban design under various wind speeds and geometric factors and the findings also indicated that the canopy diameter has a greater influence on stress and strain compared to the bole length (9). The Uproot Resistance Index (URI) for wind force uprooting resistance based on the tree shape, which regulates the applied moment on the root system and the root-plate size influencing the uprooting strength were discussed (10). In India, coconut production is the secondary crop of the state after rice, which is considered to be the primary food grain. Fourteen lakh coconut trees were uprooted and nearly 50,000 coconut farmers in the state have been impacted by Cyclones like Fani, Gaja, etc (11, 12). Figure 1 (A) and (B) show the images of coconut trees damaged during cyclones. This loss will undoubtedly impact the agricultural economy because it will be difficult for them to recover from this setback. So, to overcome this, CFD provides a vital platform for accurate analysis and prediction. The present study focuses on analyzing wind flow dynamics surrounding coconut trees arranged in two different planting patterns - uniform and staggered arrangements, by using CFD and investigating the variation of pressure distribution around the two different patterns of coconut tree canopies. The main objective is to model and examine the wind flow behavior around and within the coconut tree canopies during cyclone events, focusing on understanding the patterns of turbulence and wind stress that contribute to tree damage. The key findings offer a foundation for developing strategies to minimize cyclone-induced damage to trees, contributing to more resilient agricultural practices in cyclone-prone regions.

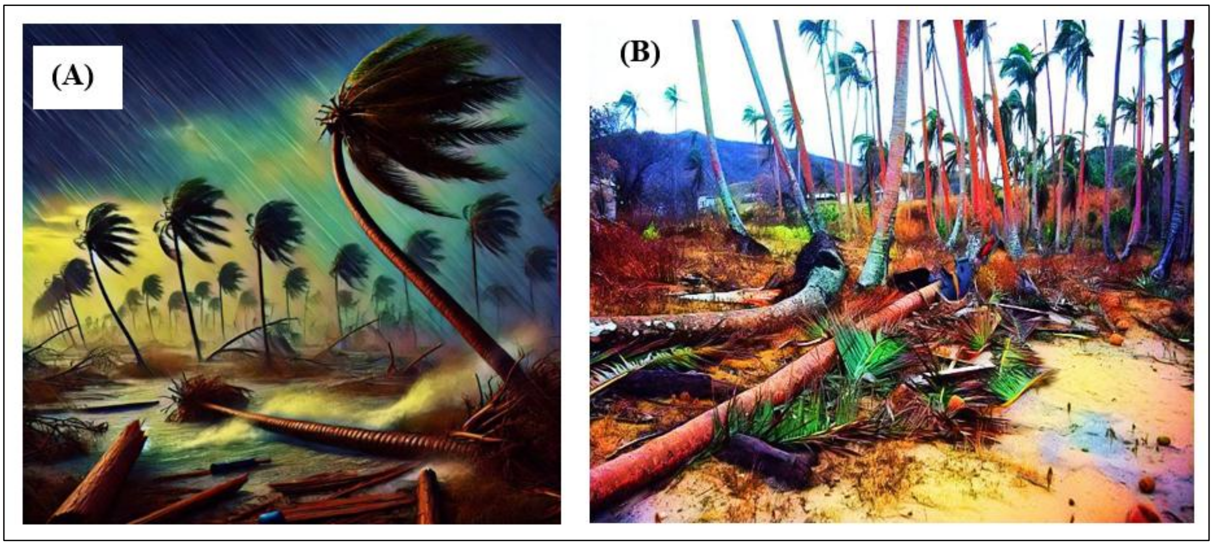


Figure 1: (A) and (B) Coconut Trees Are Damaged Due to Cyclones at Different Places

Methodology

The CFD methodology process consists of a series of steps by defining a problem till interpretation of the results. Care must be taken at every stage to ensure accurate and reliable simulations, from the creation of models and meshing geometry to choosing the best physical models and boundary conditions. Figure 2 demonstrates the methodology of wind flow around trees, which involves three phases: pre-processing, solving, and post-processing.

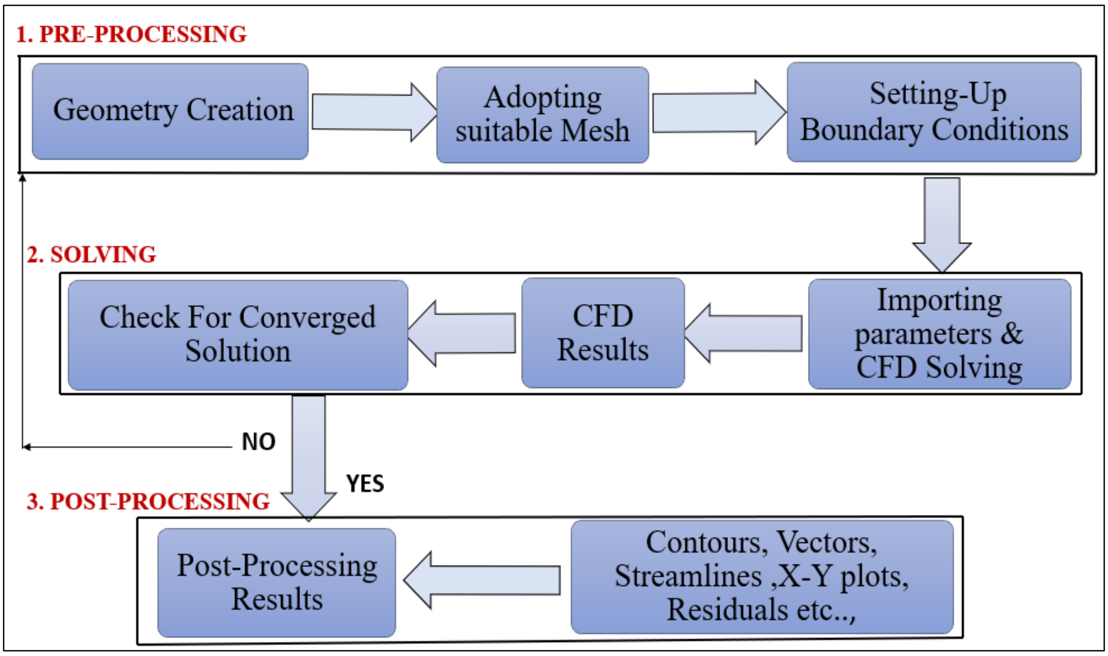


Figure 2: Methodology Process of Wind Flow Around Trees

Numerical Analysis

Governing Equations: The numerical study used the Standard k-ε turbulence model available in the ANSYS Fluent software. In this two-transport equation model, the first one is the turbulent kinetic energy (k), while the rate of its dissipation (ε) is the second. To simulate the impact of turbulence on the mean flow field, these two equations are solved in conjunction with the Reynolds-averaged Navier-Stokes (RANS) equations.

The standard k-ε model's governing equations are briefly described below:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + P_k - \rho\varepsilon + P_{kb} \quad [1]$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j \varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_1\frac{\varepsilon}{k}(P_k + C_3 P_b) - C_2\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad [2]$$

P_k is the kinetic energy of turbulence generated by the mean velocity shear, P_b is the buoyancy-induced turbulence production, and S_k refers to an externally defined source term. The current study employs the constant values for the turbulence parameters as specified by the earlier researchers (13) and the values are σ_k is 1, σ_ε is 1.3, C_1 is 1.55, C_2 is 2.0 and C_μ is 0.09, respectively. For a high Reynolds number, the energy dissipation ε can be approximated as $\rho k^{1.5}/l$.

$$\mu_t = \frac{C_\mu \rho l k^2}{\varepsilon} \quad [3]$$

Where μ_t and k are nonzero, ρ is the constant air mass density taken as 1.225 kg/m^3, C_μ has a constant value of 0.09 and l is the turbulent eddies length scale.

Wind Velocity: The wind profile scale is a main parameter in CFD studies that affects boundary layer formation and turbulence modeling. Moreover, crop production depends on the arrangement of trees in canopies, so it is important to understand the wind interaction in the tree canopies, which helps in optimizing orchard design. The model was carried with wind force having a velocity of 5 m/s at a wind angle of 0°. The wind velocity varies more with the height of trees and is lower on the ground surface. To accurately depict the stresses caused by cyclones, realistic wind effects were simulated using a velocity scale ratio of 1:5. Tree stability and vortex formation are greatly impacted by turbulent airflow, which is confirmed by the Reynolds number (*Re*).

Scale Parameters: In the present study, modeling a tree within a tree canopy, along with the individual leaves, poses significant challenges. Therefore, the tree canopy is represented as a circular cross-section in two dimensions (2D). This model is incorporated into the computational domain, which is a region of wind flow, where the fluid flow equations are solved using finite element operations. The modeling parameters remain consistent for both uniform and staggered arrangements. Table 1 provides details of modeling scale parameters for both patterns.

Table 1. Modeling Parameters for Both Cases

Sl. No.	Scale Parameters	Scale Dimensions
1	Length scale	1:100
2	Velocity scale	1:5
3	Upstream length (l_u)	5 D
4	Downstream length (l_d)	15 D
5	Side clearance (b)	5 D
6	Diameter of the circular tree (D)	15 cm
7	Dimensions of the domain	7.05 m × 5.55m

Computational Domain Size and Boundary Conditions: The computational domain was set up as a digital orchard forming a 2-D model with length (L) of 7.05 m along the X-axis and width (B) of 5.55m along the Y-axis, respectively. The domain dimensions are shown in Figure 3. The main domain consists of a series of 7 rows and 7 columns of coconut trees, such that a total of 49 trees are there. The spacing of trees between columns and rows of the 2D simulated orchard was 50 cm. The domain size reference is taken from a suggestion presented by authors (14, 15). It extends upon 5 D up face, 15 D down face, and 5 D laterally sideways from the tree, where 'D' is the diameter of its circular cross-section of the tree. The domain size that has been chosen is more than sufficient to allow for wind-induced vortex formation and backflow. The inlet boundary condition for this study is given as 5 m/s, and the outlet boundary condition is 0. No-slip wall is accounted for on the floor of the computational domain to make sure that there is no velocity between the wall and the fluid in motion. The pressure outlet boundaries were set as zero, and the free slip is taken into consideration in the top and side walls of the computational domain $\partial / \partial x\ (u, v, w, k, \varepsilon) = 0$. Figure 4 shows the 2D view of the computational domain (A) Uniform and (B) Staggered arrangement of tree barks.

T1, T2, T3, ………… T49 - Tree 1, Tree 2, Tree 3, …………Tree 49.

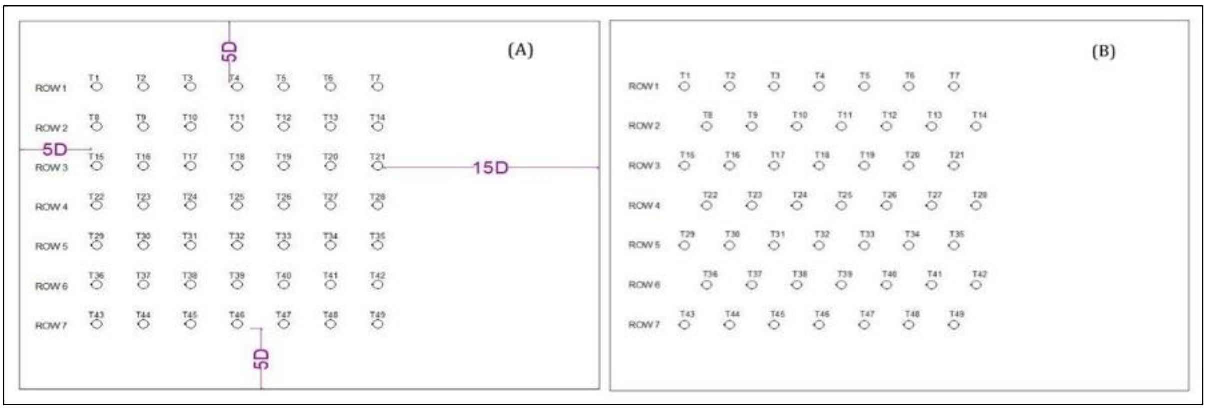
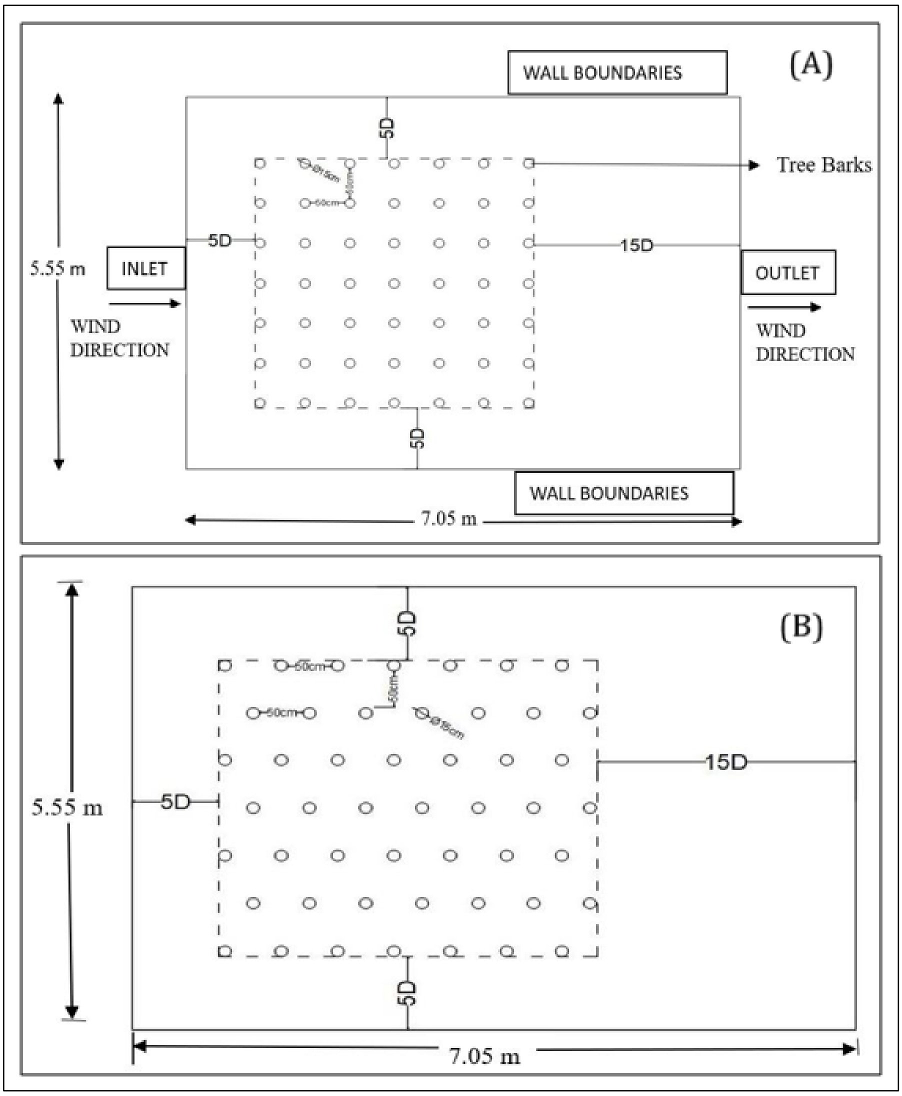


Figure 3: 2D View of Uniform and Staggered Arrangement of Tree Barks: **(A)**Uniform Arrangement, **(B)**Staggered Arrangement



Note: D- Diameter of the circular cross-section of the tree; ○ - Circular cross-section of the coconut tree (Tree Bark)

Figure 4: 2D Plan View of the Computational Domain: **(A)**With Uniform Arrangement, **(B)**With Staggered Arrangement

Meshing: The accuracy of simulation results and the efficiency of calculations are influenced by the quality of meshing. The present studies use quadrilateral meshes for simpler 2-D geometries in ANSYS FLUENT Meshing, which is appropriate for enhancing their efficiency. Following this, three sets of grid resolutions - coarse, medium, and fine were created by adjusting the various mesh sizes of each subdomain boundary. For the present study, the fine mesh size was chosen to capture the detailed airflow characteristics in both case studies.

Blockage Ratio: In the present study, the blockage ratio is nil because it is less than 5%. So, there is no need for blockage correction. The blockage correction factor is necessary if the blockage ratio is more than 5%.

Grid Independence Study and Validation: A grid independence test was performed for this proposed model to ensure an accurate solution. Three different mesh resolutions were tested: coarse, medium, and fine. Grid resolution directly influences both computational processing expenses and time requirements. For the final result analysis, the fine mesh resolution was selected for further examination because its variation in results was less than 2%. In addition, the blockage ratio was below 5%, thus eliminating any requirement for corrections in this study. These outcomes support the validation of CFD in wind stress analysis and tree plantation layout optimization to prevent cyclone damage. Figure 5 and 6 display the three sets of grid size distribution with both uniform and staggered arrangements. Table 2 and 3 show the grid sensitivity study for uniform and staggered arrangements with node and element count. Figure 7 also shows the overall mesh distribution images closer to the tree bark for both patterns.

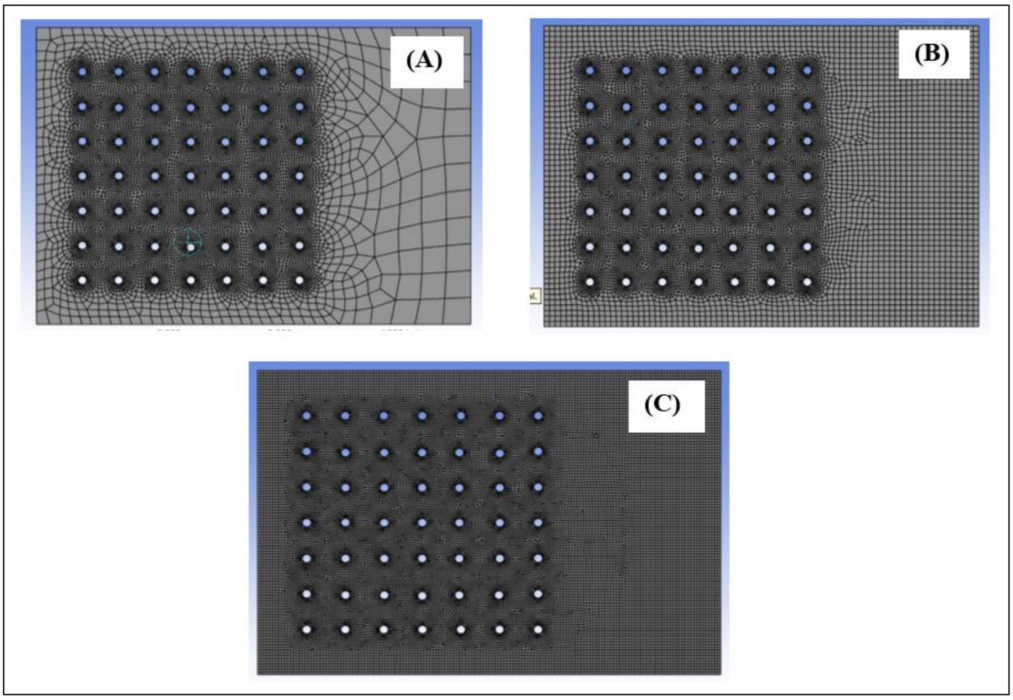


Figure 5: Overall Grid Generation Study with Uniform Pattern **(A)**Coarse, **(B)**Medium, **(C)**Fine

Table 2. Mesh Count for Case-I (Uniform Pattern)

Grid Size	No. of Nodes	No. of Elements	Δ_x(m)
Course	12931	12502	0.0025
Medium	14852	14352	0.0020
Fine	23770	23131	0.0020

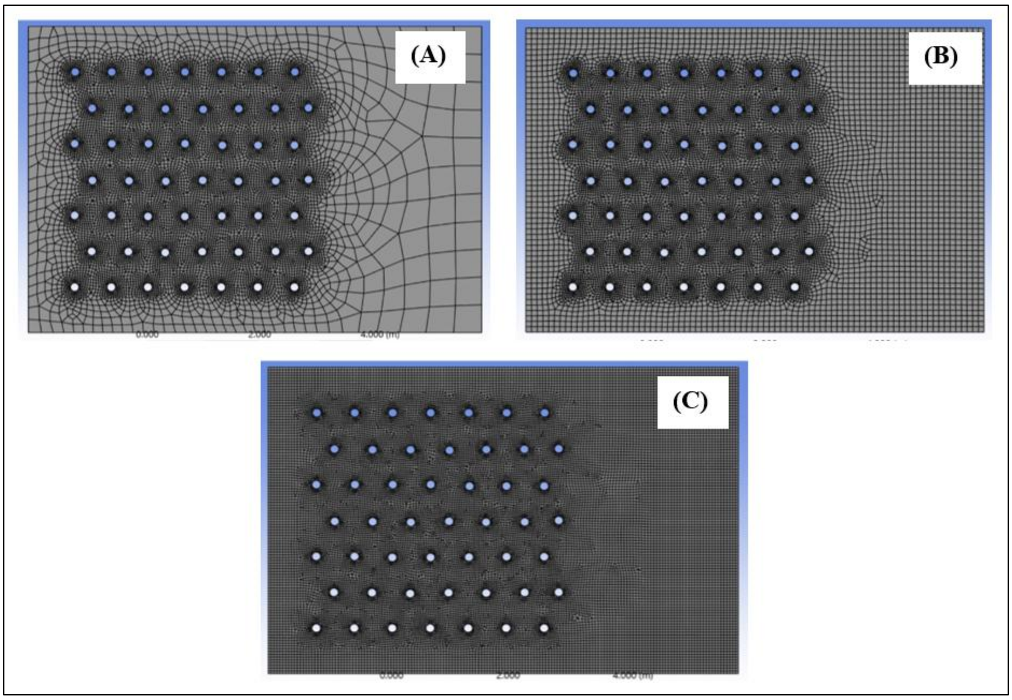


Figure 6. Overall Grid Generation Study with Staggered Pattern **(A)**Coarse, **(B)**Medium, **(C)**Fine

Table 3. Mesh Count for Case-II (Staggered Pattern)

Grid Size	No. of Nodes	No. of Elements	Δ_x(m)
Course	12771	12351	0.0025
Medium	14887	14382	0.0020
Fine	24138	23505	0.0020

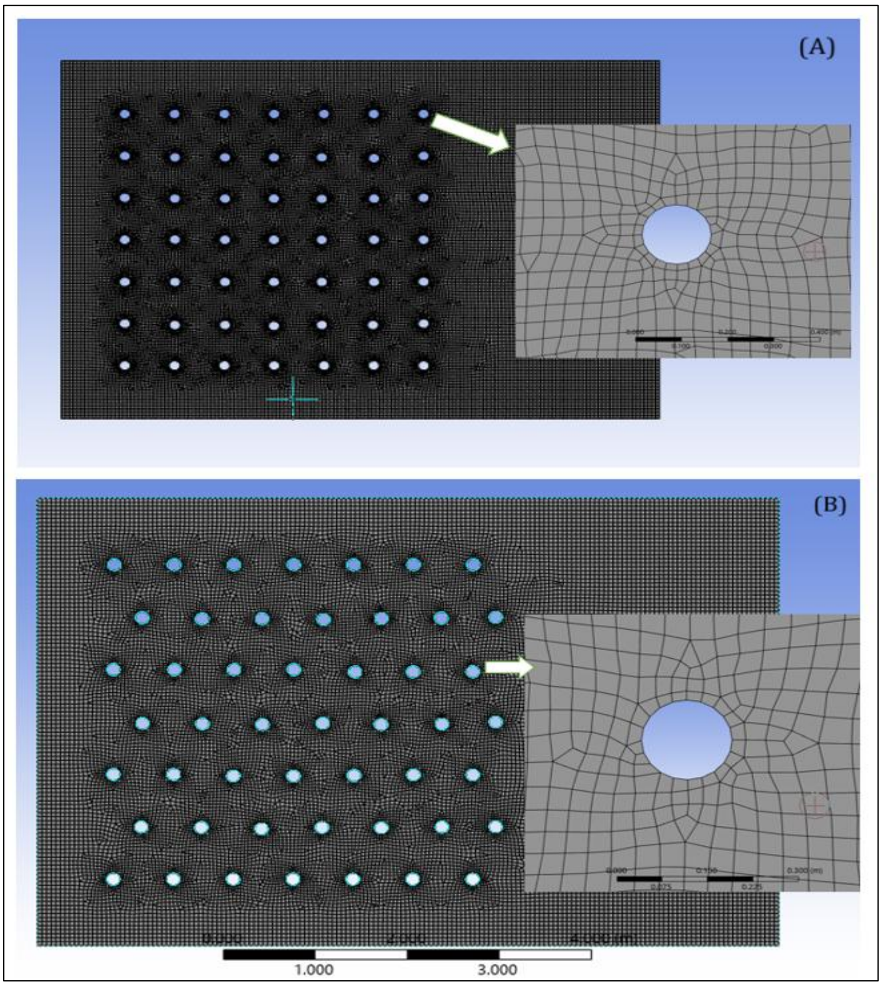


Figure 7: Overall Mesh Distribution Showing Closer to the Tree Bark **(A)**with Uniform Pattern, **(B)**with Staggered Pattern

Solver Settings: The CFD simulations are carried out with a commercial program ANSYS FLUENT solver, which is incorporated with the Ansys software package. The control equation was discretized using the finite volume method (FVM) to solve the transient airflow field. The problems are solved in an Intel 9th Generation Core i7 processor serves as computer hardware. The Reynolds-averaged Navier-Stokes (RANS) equations, the most popular averaging technique and most cost-effective method for solving fluid phase problems, and the Standard k-ε turbulence model were used in this study. The side boundaries in the windward and main domains were designated as velocity-inlet and pressure-outlet based on the direction of the wind. The wind velocity of 5 m/s is applied at the inlet with a wind angle of 0° in the direction of the wind. Table 4 shows the parameters used in the solver setting process.

Table 4: Solver Settings for Both Case Studies

Sl. No.	Parameters	Solver Setting
1	Solver scheme	Pressure-based velocity coupling solver
2	Turbulence model	Standard k-ε model
3	Spatial discretization	Second order-upwind

4	Temporal discretization	First Order Implicit Method
5	Pressure-velocity coupling	SIMPLE Algorithm Method
6	Inlet boundary condition	Uniform velocity - 5 m/s
7	Outlet boundary condition	Zero-gradient pressure
8	Time step size	0.005 s
9	Iterations per time step	10
10	Total number of iterations	1000

Results and Discussion

Pressure Distribution inside Domain

The CFD result demonstrates how the wind blows around the coconut trees and creates a vortex formation. At the inlet, a wind speed of 5 m/s is applied at a wind angle of 0°. On the wind-facing side of the coconut tree, positive wind pressure is formed, and on the wake region side, high negative pressure is formed. The coconut trees sway to a great extent during a cyclone because their varying pressure distribution differences between these two sides. The aerodynamic features of coconut trees are usually tall, flexible, slender and because of their porous structure and how their crown streamlining changes their geometry with wind speed. Figure 8 and 9 display the airflow distribution pattern around the trees in both uniform and staggered arrangements.

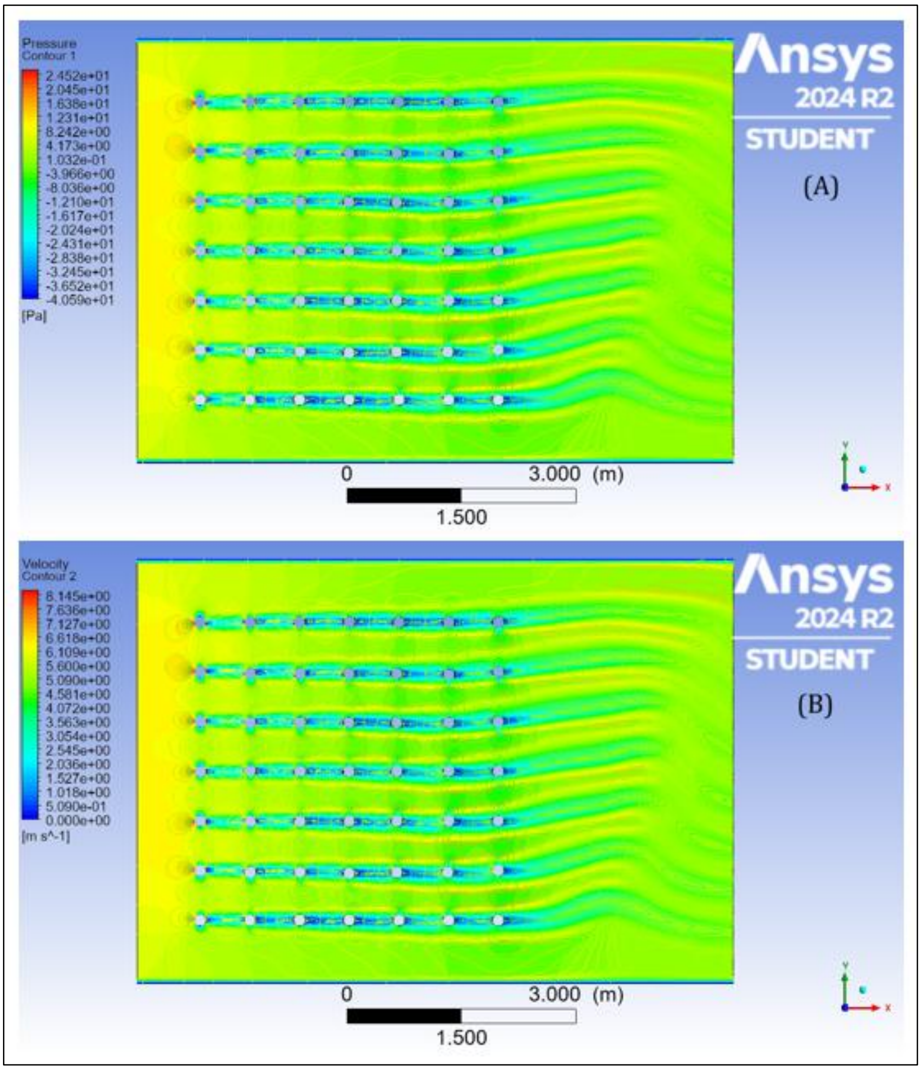


Figure 8: Wind Flow Pattern around Trees in Uniform Pattern **(A)**Distribution of Wind Pressure, **(B)**Distribution of Wind Velocity

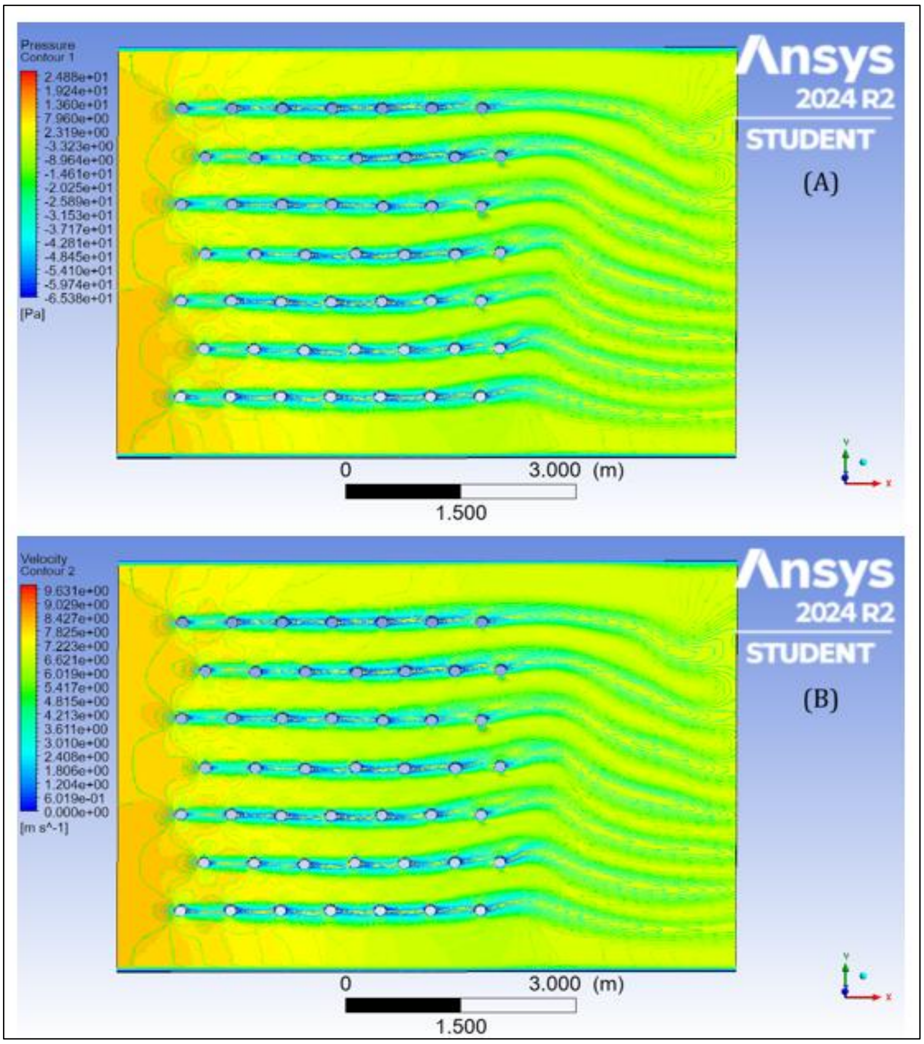


Figure 9: Wind Flow Pattern around Trees in Staggered Pattern **(A)**Distribution of Wind Pressure, **(B)**Distribution of Wind Velocity

Vertex Formation

A frequent occurrence in wind interactions with obstructions, the models showed the creation of vortices behind the trees. In a uniform pattern, these vortices were stronger and more widely dispersed, which could have increased wind-induced oscillations and damage. The noticeable vertex formations downstream of the tree canopies in uniform patterns indicate a higher level of turbulence intensity. This phenomenon, especially during extended cyclonic events, increases the probability of fatigue stresses and dynamic oscillations on the trees.

Vertex formations were disturbed by the staggered arrangement, which led to weaker and more confined turbulence zones. This decrease in turbulence intensity directly lowers aerodynamic drag and reduces the chance of dynamic response that coconut trees will experience structural failure. Many authors highlighted that optimal planting patterns could reduce dynamic deformation and wind-induced stress, while small deformation stresses are insufficient to capture wind-induced damage. The less noticeable vortices in a staggered pattern suggest that the planting arrangement lessened the force of wind eddies and, as a result, the wind's overall impact on the trees.

Comparison of Pressure Variation for Each Row

The difference is observed between the windward and leeward sides regarding the pressure distribution around the trees. Figure 10 compares the variation of pressure distribution under different row conditions for uniform and staggered patterns.

Pressure and Airflow Distribution

The pressure distribution in a uniform pattern showed greater positive values on the windward side, which caused the leeward side's pressure to drop significantly and resulted in the creation of negative suction pressure zones. This pattern implies that trees arranged in this way are more vulnerable to stress and perhaps harm from the wind. But in a staggered pattern, the leeward side's negative pressure was less noticeable. This suggests that there is more equilibrium in the airflow surrounding the trees, which lessens the possibility of extreme wind stress. This indicates more balanced airflow around the trees, reducing the potential for extreme wind stress. The staggered arrangement of the trees allowed the airflow to dissipate energy more gradually as it passed through the orchard. The downstream rows reduced Turbulence Kinetic Energy (TKE) values and smoother velocity profiles make this clear. The downstream rows in the uniform arrangement had high residual turbulence, which led to chaotic airflow patterns in those rows. So that the staggered layout effectively mitigates the wind-induced stress by redistributing the airflow evenly.

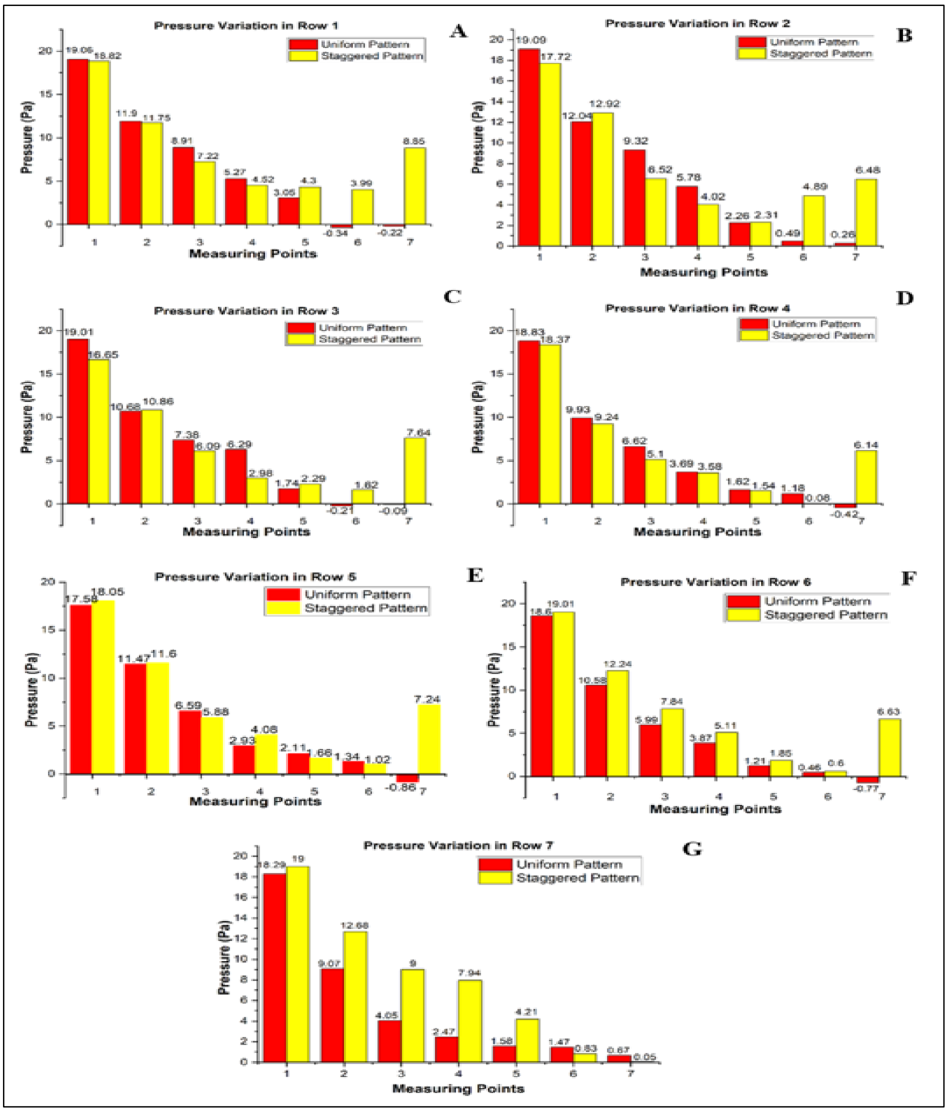


Figure 10: Pressure Variation in **(A)**Row1, **(B)**Row2, **(C)**Row3, **(D)**Row4, **(E)**Row5, **(F)**Row6, **(G)**Row7

The maximum total pressure was analyzed in a staggered pattern as a 0.83% increase when compared with a uniform pattern, indicating a more stable airflow and better resistance to wind damage. By analyzing the graphs of each row, there was a slight increase in the percentage of total maximum pressure noticed in a staggered pattern rather than in a uniform pattern. The pressure zones on the leeward side of the uniform pattern remained 15-20% lower than those of the staggered pattern, which intensified negative suction forces leading to potential structural instability. The staggered configuration reduced pressure fluctuations across rows by 30% more than typical uniform arrangements. The designed layout of the staggered arrangement of trees minimizes force oscillations in trunk and root areas and also helps to protect their structural integrity by distributing aerodynamic forces to reduce the overall stress accumulation. The findings show that, in comparison to the uniform pattern, the staggered arrangement decreased the peak turbulence energy by 25%, which lowers the risk of uprooting or stem failure.

Variation in Pressure throughout Rows

The uniform pattern revealed a notable fluctuation in pressure throughout the rows. The first few rows showed the biggest drop in pressure, with the pressure fluctuations in the following rows becoming gradually smaller. Different stress levels and possible damage could be caused by this unequal distribution throughout the orchard. During cyclonic conditions, this unequal load distribution may cause cascading failures. A more uniform distribution of wind forces over the orchard is implied by the staggered pattern's smoother pressure gradient across the rows. This staggered planting system distributed wind flow evenly across all rows by reducing variations in pressure and velocity levels. Because of this consistency, individual trees may experience less stress and become more resistant to wind damage.

Conclusion

The pressure distribution of two different planting patterns - uniform and staggered configurations are investigated using CFD with the help of the Standard k-ε turbulence model. The research findings indicate that, when compared with uniform arrangement, the planting pattern employed in staggered arrangement provides superior protection against wind stress. This approach appears to be more successful in minimizing damage caused by cyclones, as seen by the staggered pattern's less intense vortex and more even pressure distribution. In cyclone-prone areas, the staggered layout's decreased wind stresses and turbulence can greatly extend the coconut trees' lifespan and yield. Therefore, using this planting pattern could make coconut groves more resilient in areas that are vulnerable to cyclones, improving agricultural sustainability and minimizing damage during extreme weather events. The results offer useful recommendations for designing orchard layouts that shield crops from the damaging effects of strong winds and cyclones.

In order to fully understand the effects of varying wind speeds in conjunction with environmental factors, future research must concentrate on creating intricate 3D simulation models that depict various tree structures using real-time cyclone data.

Abbreviations

CFD: Computational Fluid Dynamics, FSI: Fluid Structure Interaction, FVM: Finite Volume Method, RANS: Reynolds-averaged Navier-Stokes, SIMPLE: Semi-Implicit Method for Pressure-Linked Equations, TKE: Turbulence Kinetic Energy.

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Author Contributions

Divya Chinnadurairaj: CFD simulations, data analysis, manuscript writing, Vigneshwaran Rajendran: Conception, provided guidance and ideas, reviewed the manuscript, offered corrections.

Conflict of Interest

No potential conflict of interest was reported by the authors.

Ethics Approval

This study involves computational simulations and does not require formal ethical approval. All research was conducted following ethical guidelines.

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