Review

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# Advances in methodologies to assess wind actions in plastic-covered greenhouses

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**ABSTRACT**: The technology provided by greenhouses is essential for protecting crops sensitive to bioclimatic adversities and for improving agricultural production indexes. However, the need to know the exact interaction between the flexible coating and the structure under wind action has motivated new studies. The objective was to perform an in-depth review of the scientific and technological advances regarding methodologies to obtain parameters related to wind actions that are essential for the structural safety of greenhouses. This study showed the relevance of experimental methods; however, the limitations of the study are diverse, as field experiments require the construction and modifications of a prototype, which demand time and financial resources. Experiments in wind tunnels with models on a reduced scale have contributed significantly, as it allows to control the wind flow; however, in plastic-covered greenhouses, discrepancies occur due to the impossibility to represent the aeroelasticity of the construction. Modeling via computational fluid dynamics (CFD) has proven to be a solution for extrapolating limitations in experimental methods by facilitating changes in the construction model and wind flow. In addition to pure turbulence models, studies on hybrid turbulence models (Scale-Resolving Simulation) must be deepened to obtain greater accuracy of pressure coefficients. The complexity of the subject and the need for new contributions to plastic-covered greenhouse projects are a reality, which outlines a promising horizon for research development in the rural construction sector.

**Keywords**: protected cultivation, wind tunnel, finite element method, computational fluid dynamic, fluid-structure interaction

## Introduction

Greenhouses are rural constructions to protect crops from local weathering and several pests. These buildings are increasingly embedded in technologies housing high-tech equipment to provide a suitable production environment for several crops, such as flowers, fruits, and vegetables (Ghoulem et al., 2019; Shamshiri et al., 2018). As a protection and comfort measure for crops, it is recognized worldwide that greenhouses have enabled an increase in productivity and a seasonality extension of crops, which further stimulates the use of this cultivation technology (Briassoulis et al., 2016; Giacomelli et al., 2008; Giacomelli et al., 2019; Iddio et al., 2020; Morgan, 2021; Kaur and Dubey, 2019; von Elsner et al., 2000).

Greenhouses are permanent structures for crop protection and comprise low tunnels (comprising flexible arches less than 1 m high) and rows or floating covers to protect plants mainly against insect attacks and wind actions, which are typical for the cultivation of creeping plants, such as melon, watermelon, and strawberry (Dorais, 2019; Jayasurya et al., 2021). In addition, there is a growing concern about food security to meet the demand for population increases amid a climate change scenario (Briassoulis et al., 2016; Gruda et al., 2019; Lawrence et al., 2015).

Production efficiency of a greenhouse depends on the coating material, which must be adequate to transmit solar radiation to the crop and ensure energy conservation while meeting the requirements for strength, quality, and safety. The choice of coating material is defined according to the local climatic conditions, the type of crop to be produced, durability, and, especially, the cost of the material (Ghoulem et al., 2019; Shamshiri et al., 2018). Currently, three types of covering meet the demands of producers of protected crops: glass, plastic film, and rigid plastic panels (Mefferd, 2017). The use of plastic film in greenhouses has intensified since the 1950s, and its use has surpassed 90 % of the other types of covering materials worldwide, mainly due to economic reasons (Kittas et al., 2017; Parlato et al., 2020). Plastic film coverings meet the needs of solar radiation, and this material has brought an innovative aspect to greenhouses that can be easily designed as arch-shaped (Scarascia-Mugnozza et al., 2012). Following the global trend, in Brazil, most greenhouses are coated with plastic film (low-density polyethylene - LDPE) and the growth of this sector is attributed to incentives, such as the Plasticulture Subsidy Program led by the government of São Paulo State (Faria Junior and Hora, 2018).

The greenhouse shape and the support of its coating material require structures designed using traditional building materials, such as carbon steel, galvanized steel, aluminum, and wood (Ponce et al., 2014; von Zabeltitz, 2011), which are chosen according to their mechanical properties and regional market availability. Truss-type light structural systems and frames with metallic tubular profiles are widespread because of the need for significant penetration of solar radiation into the environment. Various shapes can be designed to meet regional particularities, such as climate zones and different crops (Figure 1). For example, the parral type with a flat roof is widely used in southern Spain, while in China, the type with an opening for solar radiation on only one side is common (Chinese solar type). In Brazil, most commercial greenhouses are of the gabled or arched type, manufactured with galvanized carbon steel profiles or extruded aluminum profiles.

The use of plastic film as a covering material for greenhouses, along with a light structural system, results in a light and flexible construction, whose leading cause of structural damage has been adverse climate actions, such as intense winds (Bronkhorst et al., 2017; Kwon et al., 2016; Moriyama et al., 2008; Singh et al., 2021; Uematsu and Takahashi, 2020; Wang et al., 2021; Yun et al., 2014a). The wind is considered one of the root causes of accidents in greenhouses. Knowledge of the distribution of pressure coefficients ($c_p$) is mandatory for the appropriate interpretation of the mechanical behavior of the construction type and the development of safe designs (Moriyama et al., 2015).

Regardless of the type of material used, the greenhouse structure should be designed according to safety criteria to meet the combinations of all predicted loads. The structure self-weight, the coating material weight, and technological equipment are inherent in construction and wind action, maintenance, crop load suspended in parts of the structure, and if applicable, snow action should be considered (Jiang et al., 2021; McCartney and Lefsrud, 2018; von Elsner et al., 2000; von Zabeltitz, 2011; Wang et al., 2021; Yun et al., 2014b).

Full-scale experiments carried out to obtain the pressure coefficients in greenhouses with different roof shapes (Hoxey and Richardson, 1983) have contributed significatly to the development of the design methodology. However, the condition of natural ventilation does not provide critical data on the causes of structural damage to the greenhouses or even the detachment of the plastic film from the structure. Commonly, to evaluate the more severe wind effects, a rigid small-scale model is built to be assessed in a wind tunnel (Bronkhorst et al., 2017; Pakari and Ghani, 2019; Robertson et al., 2002; Yang et al., 2013). In the case of roofs with a rigid material (e.g., glass), the external pressure coefficients can be more easily applied in projects and extracted from the various standards worldwide that address wind action. Experiments carried out in a wind tunnel to investigate the horizontal wind force in multi-span greenhouses showed inconsistencies with standards EN 13031-1 (European Committee for Standardization – CEN, 2001) and EN 1991-1-4 (CEN, 2005), especially when considering an increase in the number of spans (Bronkhorst et al., 2017).

Greenhouses coated with a flexible material (plastic film) have a more complex wind behavior since the airflow instantaneously modifies the plastic film shape, thus implying an interaction between the coating and the structure. Significant difficulties in validating the present study lie in the lack of statistical data and

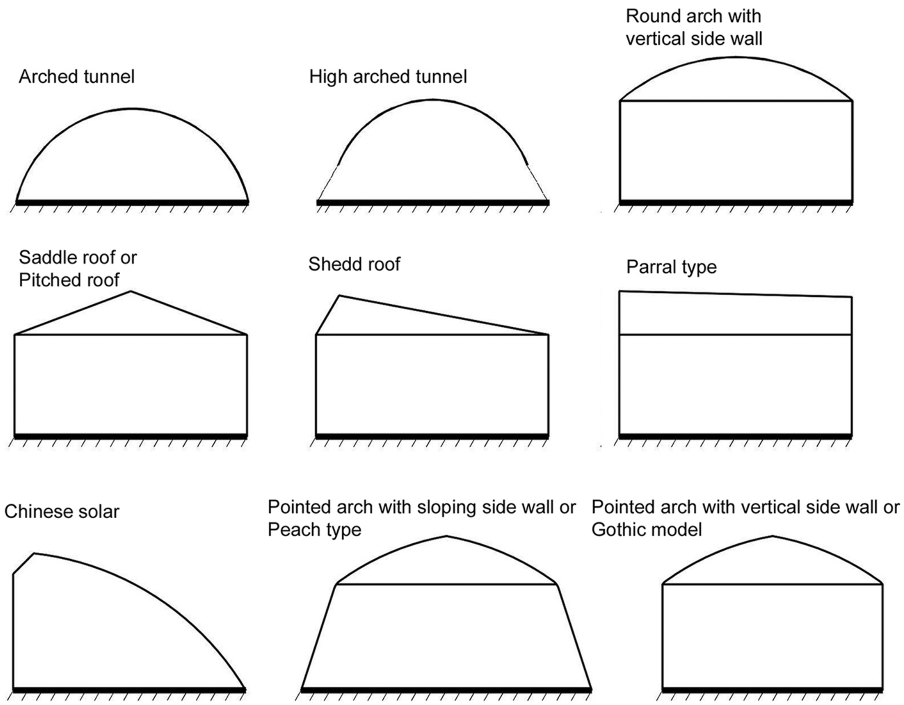

**Figure 1** – Different shapes of greenhouses.

no consideration of aeroelasticity to configure the distribution of the pressure coefficients in greenhouse models with plastic covers in a wind tunnel, considering the theoretical values of minimum critical wind speed (Yang et al., 2013).

Computational technology is a crucial tool for engineering projects to overcome the inherent limitations of evaluating experimental models, mainly due to the cost and time required for repetitions. Limitations occur in both full-scale and wind tunnel experiments. Using computational fluid dynamics (CFD) is advantageous due to the wide flow variables essential for the development of engineering projects (Bendjebbas et al., 2016). It is possible to control the internal environment of the greenhouse due to the facilities of the CFD models concerning the results obtained with field limitations with the model validation by the characteristics of the wind flow, construction, and crop (Yeo et al., 2022).

However, accuracy of the numerical simulation results to the experimental data of a problem strongly depends on the applied turbulence model since the distribution of wind pressure is influenced by phenomena arising from the aerodynamics of the greenhouse construction, such as stagnation and separation of fluids, reconnection, and vortex (Meng et al., 2018). Thus, validation of computational methods is necessary since there is no universal turbulent model (Králik et al., 2017), as demonstrated by the numerous works that tested and confronted the results of variations in wind flow related to the greenhouse building characteristics and its surroundings. Several contributions and stimuli for the use of this computational tool can be seen in the analysis of pressure coefficients in greenhouses (Kim et al., 2017; Mathews and Meyer, 1987; Mathews et al., 1988; Mistriotis et al., 1997; Reichrath and Davies, 2002; Vieira Neto and Soriano, 2020; Wang et al., 2021).

Few studies have analyzed the interaction behavior between the plastic cover material and the structure of the greenhouses. A study was carried out based on the finite element method (FEM) on the plastic strength due to wind suction action. However, it did not evaluate the transmission of forces and possible damage to the greenhouse structure (Dougka and Briassoulis, 2020). The analysis of the dynamic effects of wind load in greenhouses has been a concern for researchers, such as the effects of its fluctuations (Wang et al., 2022). In case studies with FEM of a type of greenhouse called Chinese Solar Greenhouses, the authors showed by the harmony superposition method that fluctuating wind loads may require a coefficient value of 2.0 for the global nodal displacement. The dynamic response in the structure due to wind, including the effects of coating fluctuation, has been studied; however, the structure-cover interaction still needs to be addressed (Jiang et al., 2021). Although little explored due to its complexity, the fluid-structure interaction (FSI) should be considered for the behavior of the simulated structure to be the closest to and the most compatible with reality (Uematsu and Takahashi, 2020).

This review aimed to contribute to the knowledge of experimental methodologies (in the field or wind tunnel) and possible computational solutions to better understand the mechanical behavior of plastic-covered greenhouses under wind action. For this type of rural construction, due to dynamic wind conditions, several effects occur that are admittedly complex and inherent to the type of lightweight structure and flexible cover. The evolution of computational methods is characterized by the various proposals for turbulence models, meshes, and control volumes applied in simulations to overcome the limitations of experimental methods. In this study, we recognize a need and tendency to develop computational models that represent more accurately the phenomenon of fluid-structure interaction in greenhouses. Thus, this review carried out an in-depth analysis of scientific and technological advances regarding methodologies to obtain parameters related to wind actions essential for the structural safety of greenhouses.

## General aspects related to the design of greenhouses

Greenhouses are designed to create an environment that enables control solar radiation levels, temperature, humidity, and carbon dioxide concentration to provide the ideal setting for crop development (Kendirli, 2006). The investment policy in the building of protected cultivation greatly contributes to the challenge of increased consumption as a result of the growth of the world population and climate change, which implies losses to the agricultural sector (Briassoulis et al., 2016; Kim et al., 2021; Lawrence et at., 2015).

Designs with light structural elements and the use of low cost materials to form the structural systems of the greenhouses are recommended (von Zabeltitz, 2011). Light structural systems, such as trusses or arches, are commonly made of wood or steel (Figures 2A and 2B). However, there are also proposals for the use of unconventional materials for greenhouse structures in the literature, such as the use of bamboo (Mendez et al., 2017) or profiles of material composed of recycled polyethylene terephthalate, nylon and fiberglass (Tsai and Lee, 2021).

Concepts of greenhouse design can be grouped into two types: following local or international standards or encompassing low-cost temporary greenhouses (Briassoulis et al., 2016). Greenhouses are commonly built with wooden structures for the latter group and applied in small rural properties. In this case, aspects of safety and recommendations imposed by the specific standards for this type of structure are often disregarded. When built based on experience and empirical knowledge, protected cultivation facilities can result in oversized structures and costly constructions (Faria Junior and Hora, 2018). Greenhouses built based on empirical knowledge may not withstand loads and culminate in their mechanical collapse (Ren et al., 2019).

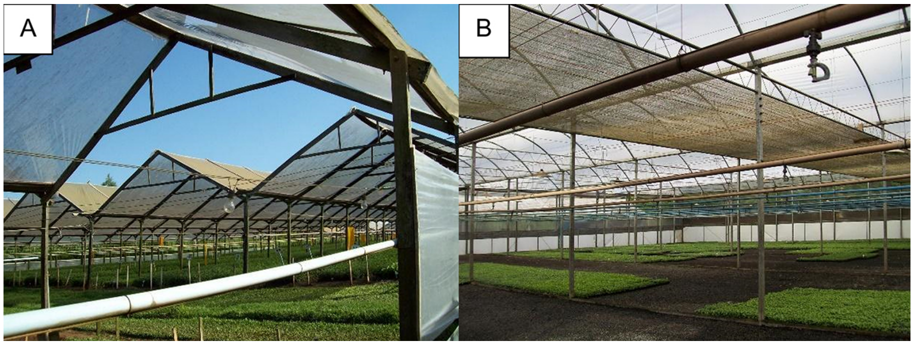

**Figure 2** – Greenhouses covered with plastic. (A) Wooden structural frame; (B) Steel structural elements.

The structural design of the greenhouse is crucial. It must be elaborated to meet the safety criteria to withstand all expected loads without causing damage to the construction and the crop, the equipment, and the workers involved in the activities. Therefore, in addition to the permanent loads (self-weight of structural members, coverage material, fixed equipment), the structure must be built to withstand variable actions, such as wind and loads related to the crop (when applied), storm, hail, and snow (when applied) (Aldrich and Bartok, 1994; von Zabeltitz, 2011). Attention is required when considering accidental actions, given the large number of records of structural damage in greenhouses caused by strong winds and snow, with economic and crop losses, which can lead to the bankruptcy of horticultural companies (Briassoulis et al., 2016; Moriyama et al., 2015; Peña et al., 2020; Ryu et al., 2019; Wang et al., 2021).

Regarding reliability and safety of the structure design, wind action is complex due to uncertainties of a natural phenomenon, which are attributed to periodicity, speed and wind direction, location, topography, and pressure coefficients (Holmes, 2004; Zhao and He, 2017). In the case of plastic-covered greenhouses, the wind action is described as the leading cause of damage to both the coating and the structural elements; therefore, for economic and safety reasons, the effects of wind action should be adequately considered in the projects (Briassoulis et al., 1997; Mathews and Meyer, 1987; Mistriotis and Briassoulis, 2002; Yang et al., 2013). Among the structural damages caused by the action of intense winds, the collapse of the entire structural system is the primary concern, also destruction of parts of the structure, failure of connectors, buckling of arches, and lifting of the columns due to failures near the foundation. The single-span greenhouse composed of wooden columns and an arched steel roof structure that collapsed due to wind action (Figure 3) shows the susceptibility of the construction that culminated in the instability of the arches and failure of the purlins, as well as rupture of the plastic film. The accident occurred during a powerful storm in the spring when winds of up to 115 km $h^{-1}$ were recorded in a neighboring radius of 70 km from the site, in a part of the Brazilian territory where the basic wind speed for structural projects is equal to 162 km $h^{-1}$.

**Figure 3** – Single-span greenhouse with the arched roof collapsed by the wind action.

Damage to the structural systems of greenhouses usually occurs when the elements are not sized to withstand a given force intensity due to the wind (Briassoulis et al., 2016). Therefore, it is essential to know the pressure coefficients in the force distribution due to the wind action in each part of the structure to ensure that the designs withstand the combinations of actions (Moriyama et al., 2015).

## Greenhouse standardization

The greenhouse design requires that the structural system elements be dimensioned and verified to ensure the construction's safety, functionality, and durability. The standards, which specialized committees periodically review, are fundamental for calculating parameters and procedures to meet the standards established by a single country or a group of countries (Table 1). Many countries have published standards highlighting that this type of rural construction requires specific and/or complementary approaches to those contained in the general standards developed for civil construction. Standards followed by different countries have different parameters for wind load that is explained, for example, by the different types of shapes, which directly imply the structural safety of the greenhouse. A comparative

**Table 1** – Standards for the design of greenhouses.

| Country/Continent | Standard | Reference |
|---|---|---|
| Brazil | NBR 16032 - Structure of greenhouse and nursery farms - Requirements for design, construction, maintenance, and restoration. | (ABNT, 2012) |
| Canada | National Farm Building Code of Canada. | (NRCC,1995) |
| China | GB/T-51183-2016 - Code for the design load of horticultural greenhouse structures. | (GB/T, 2016) |
| Europe | EN 13031-1: Greenhouses - Design and construction - Part 1: Commercial production greenhouses. | (CEN, 2019) |
| India | IS 14462 Indian standard. Recommendations for layout, design, and construction of greenhouse structures. | (IS, 1997) |
| Japan | Standard for structural safety of greenhouse. | (JGHA, 2016) |
| Mexico | NMX-E-255-CNCP-2013 - Greenhouses with plastic covers - design and construction - specifications. | (CNCP, 2013) |
| United States | International Building Code, which adopts parts of ASCE SEI 7-22- Minimum design loads and associated criteria for buildings and other structures.<br>Structural design manual. | (ICC, 2021)<br>(ASCE, 2022)<br>(NGMA, 2013) |

study of the parameters from different standards (Kim et al., 2019a) evaluated structural safety in two types of single-span greenhouses (pitched-roof roof and vaulted roof). In identical conditions under strong wind, vulnerabilities were highlighted for the pitched-roof greenhouse in the evaluation with the parameters from Korea's and the United States' standards. In the case of the vaulted-roof greenhouse, vulnerabilities were noted for the case studies with the standards in China, the United States, and the European Union (Kim et al., 2019a). The importance of using criteria to design greenhouses is recognized in the literature, such as the European standard EN 13031-1 (CEN, 2001); however, the requirements for modeling the three-dimensional structure still need to be established (Briassoulis et al., 2016). Another area for improvement is the estimation of loadings, as the application of reduction factors can lead to underestimated loads due to the elevated level of uncertainty.

In Brazil, some pioneering studies were conducted to evaluate the distribution of external pressure in greenhouses with gable roofs and its effects on structural safety due to the roof slope, as well as the ratio between greenhouse height and span (Vieira Neto and Soriano, 2016). Based on the parameters of the Brazilian and European standards and using the FEM analysis, the present study revealed differences between the normal stresses in the structure using these standards, especially for higher roof slopes and for a higher ratio between greenhouse height and span. A comparative study of the use of parameters from Chinese and European standards was carried out by Lewei et al. (2013). Although both standards have an approximation in the distribution of pressures, the results of internal forces calculated according to the European standard proved safer, which was attributed to the more significant specificities considered, such as turbulence (Lewei et al., 2013).

In the case of multiple greenhouses, the number of spans is also to be considered for using standardized pressure coefficients. The evaluation of this parameter in a multi-span duo-pitch greenhouse showed inconsistencies in the pressure coefficients with an increasing number of spans (Bronkhorst et al., 2017). Using normalized pressure coefficients for agricultural greenhouses requires considering uncertainties of the behavior from the covering material, in addition to the limitations due to large extensions that need a large number of spans, as well as the different possibilities of types of shape (Figure 1). Plastic films, which have their shape modified by airflow, require a deeper understanding of the mechanism of their interaction with the wind, whose details are still restricted by standards such as those addressed in CEN (2019).

## Experimental models

In experimental methods, the approaches stand out regarding field tests, which are carried out with full-scale prototypes, and experiments in a wind tunnel, usually with reduced-scale models. Despite the great importance of interpreting wind action on buildings, both methods have many particularities and limitations. This section contains the main contributions to understanding the advantages and limitations of experimental methods applied to greenhouses.

The geometric shape and type of the coating material of the greenhouse are relevant for the dynamic pressure distribution resulting from wind action. Tests were carried out in greenhouses with plastic covers built at full-scale to understand how the shape of the greenhouse influences the airflow separation and, consequently, generates the pressure and suction regions (Hoxey and Richardson, 1983). Their study was one of the pioneers for this purpose and thus contributed to the development of a methodology for the evaluation of pressure coefficients. However, the natural ventilation condition did not allow to obtain data for possible critical situations that cause structural damage or even the detachment of the plastic film from the structure. In addition, in full-scale experimentation, performing tests is costly because of the greenhouse construction and the instrumentation required for data acquisition. In this case, the meteorological conditions cannot be repeated and future constructions around the greenhouse may modify the experimental conditions by the vicinity effects (Wang et al., 2021).

The effects of windbreaks were evaluated in full-scale experiments and compared to the barrier-free greenhouse, with a reduction in the difference in the external and internal pressure coefficients in the region of the windward roof (Richardson, 1986). The presence of windbreaks reduced the asymmetry of the load distribution and caused an increase in overpressure on the leeward face compared to greenhouses without windbreaks. Due to the particularities of the experimental conditions, the author highlights that the results are limited to use in other types of greenhouses, reiterating the discussions about the limitations to perform tests at full scale.

Regarding the covering material of greenhouses, great emphasis is given to the use and complexity of flexible materials, such as plastic films (Briassoulis et al., 1997; McCartney and Lesfrud, 2018; Ponce et al., 2014; von Elsner et al., 2000). The use of plastic in agriculture is increasing (von Zabeltitz, 2011) and has stimulated studies to evaluate the structural behavior of plastic-covered greenhouses. An interesting aspect evidenced by Richardson (1986) is the load transfer behavior due to the flexibility of plastic film, which is fixed only at its edges. In the suction region, the film tends to detach from the structure, causing an overpressure in part of the structure positioned in the windward region.

The EN 13031-1 standard (CEN, 2019) establishes, for arch greenhouses (tunnel type), an iterative method for the plastic film behavior displaced by suction, which is also influenced by the action of fixing the film on some of the structural members. During the greenhouse construction phase, the pre-tension applied to the plastic film causes a uniform overpressure action on the arch (Figure 4A). Wind action generates overpressure and suction actions on the plastic film (Figure 4B). The combined actions of pre-tension and wind result in the loading of the arch (Figure 4C); consequently, a portion of the suctioned film plastic loses contact with the supporting arch (Figure 4D). This behavior occurs because, in most cases, the plastic film is fixed in the arches of the extremity and along the gutters (Dougka and Briassoulis, 2020). Thus, as the plastic film is connected to the structure only along its perimeter, the remaining region can suffer displacements and deformations due to the wind action. The prestressing force applied during the installation of the plastic film is a procedure to prevent it from becoming loose and hitting the structure. For that purpose, the film is tensioned in a controlled manner to prevent early mechanical damage to the covering material. Temperature conditions also influence the plastic film behavior and, therefore, the EN 13206 standard (CEN, 2020) advises that the plastic film installation should be performed according to the manufacturers' instructions in mild climate conditions, with an outdoor temperature ranging from 15 to 30 °C.

The use of transverse and/or longitudinal intermediate supports (Figures 5A, 5B, and 5C) is an option to minimize the effects of plastic film displacements. A notable improvement in the resistance of the structure to wind actions can be achieved by using some types of supports and reinforcements (Uematsu and Takahashi, 2020). However, manufacturers avoid this solution because the plastic in the region of contact with the structure becomes more susceptible to deterioration by solar radiation. In addition, using intermediate supports can make the structure more expensive (Dougka and Briassoulis, 2020).

Engineering has conducted tests in wind tunnels with models built on small scales to understand the dynamic effects of wind action, in addition to experiments produced in prototypes with a full-scale. These tests have many advantages, along with the possibility of many repetitions, as the experimental environment can be controlled, enabling the acquisition of essential data to validate computational models (Espinoza et al., 2015; Maraveas, 2020; Wang et al., 2021). However, the adjustment of the scale to represent the wind flow conditions to a full scale should consider the reduced frequencies used in wind tunnels (Jafari et al., 2019).

The effect of airflow in adjacent greenhouses, where the distance between neighboring walls is

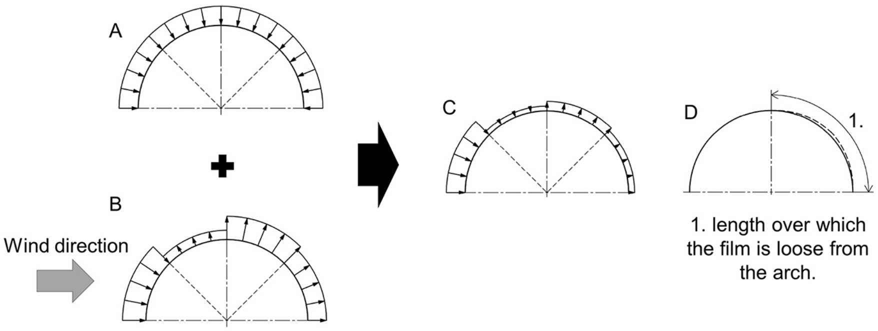

**Figure 4** – Scheme of plastic film behavior under pre-tension and wind actions (adapted from CEN, 2019). (A) Action of pre-tension applied to the plastic film; (B) Action due to wind; (C) Superposition of actions (pre-tension and wind) acting on the arch; (D) Length at which the plastic film is detached (by suction) from the arch.

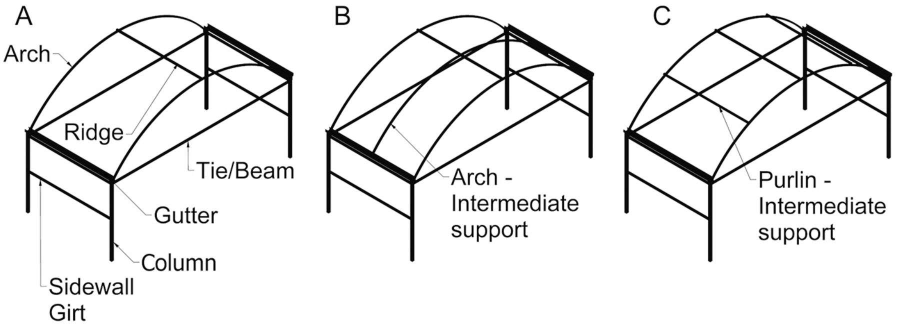

**Figure 5** – Structural scheme of an arched greenhouse module. (A) without intermediate supports; (B) with transverse support; (C) with longitudinal supports.

considered to meet the demand for luminosity by a crop, can be evaluated in wind tunnels with reduced scale models (Moriyama et al., 2010). From the analysis of the pressure coefficients and the need to evaluate the neighborhood effects, the authors concluded that, at windward, the greenhouse has $c_p$ values very similar to those of single greenhouses; however, at leeward, the $c_p$ distribution values are changed. In this case, all $c_p$ values are negative (suction), with a peak occurring near the ridge with $c_p$ values ranging from –0.7 to –1.0.

The analysis of reduced models in a wind tunnel using plastic for greenhouse covering showed that the plastic aeroelasticity effect was not considered due to the lack of statistical data on its interaction with the structure (Yang et al., 2013). Due to plastic fixation to the structure without intermediate transverse and longitudinal supports, the authors reported a lower structure resistance to critical winds. Therefore, the use of intermediate supports for the covering material is a solution to be considered in designing projects to increase the loading capacity of greenhouses.

Greenhouses of typical shapes built in Japan with sloping walls, curved eaves, and pointed ridges were evaluated with reduced models (1:20) in a wind tunnel under turbulent flow (Moriyama et al., 2015). According to the authors, these shapes promote a different distribution of the pressure coefficients and the values obtained for $c_f$ (difference between the external and internal pressure coefficients) compared to those obtained by specifications of the Japanese standard were different for an arched greenhouse and were similar for a gable roof greenhouse.

Experiments in a wind tunnel with small-scale models (1:20) were performed by Kwon et al. (2016) to evaluate the distribution of pressure coefficients in single-span greenhouses with different shapes, considering two models with straight shapes (even-span and three-quarter types) and other models with curved shapes (peach and mono-span types), covered with glass and plastic film, respectively. Due to airflow separation, the authors concluded that the most significant pressure variation is found in the eaves region. The high-pressure differences can cause permanent damage to the greenhouse structure or, eventually, the collapse of the covering material.

The possibility of generating many experiments using a wind tunnel to obtain a large amount of data is evidenced in the study by Bronkhorst et al. (2017) in which the total horizontal wind force was evaluated in gable roof greenhouses with multiple spans. The measurements of the static force in nine models of this greenhouse type show that the resulting force increases linearly with the increased number of spans and that there were no relevant changes in the roof pressure distribution from the fifth span. Experimental results compared with the coefficients given by EN 13031-1 (CEN, 2001) were conservative for the case of greenhouses with up to 20 spans, while compared with the coefficients of the EN 1991-1-4 standard (CEN, 2005) of ten spans became more conservative (Bronkhorst et al., 2017). Regarding the horizontal pressure due to the wind actions, both European standards specify negative values on the windward roof faces; however, the experiments resulted in positive coefficients (Bronkhorst et al., 2017).

Despite the inherent limitations found in wind tunnel experiments, their relevance for the validation of numerical models is evidenced in studies, as the pressure coefficients of greenhouses with variations in the slope of flat roofs and curvature of arched roofs were evaluated (Kim et al., 2019b). Correlation coefficients from 0.79 to 0.98 were obtained for pitched roof greenhouses and a range from 0.82 to 0.95 for vaulted roof greenhouses from the analysis of the results of the large eddy simulation (LES) turbulence model in CFD modeling and from studies carried out in a wind tunnel (Kim et al., 2019b).

## Computational modeling

This section addresses the benefits and limitations of the main computational methods based on fluid mechanics used in the study of pressure coefficients in greenhouses. To date, many studies have been carried out with pure turbulence models, including the Reynolds Averaged Navier-Stokes (RANS), SST k-ω (Shear Stress Transport k-omega), and Large Eddy Simulation (LES) models. Further research should be conducted with hybrid turbulence models, as is the case of the Scale Adaptive Simulation model, whose mesh changes over time to better represent the effects of the intense variations in the airflow regime during the greenhouse envelope, while reducing data computational costs.

Computational technology has provided a breakthrough for implementing digital models in all areas of engineering. Research with computational models via CFD to evaluate greenhouse pressure coefficients has been intensified and is described as essential to overcome limitations in analyses with models in the field or a wind tunnel (Kim et al., 2017; Kuroyanagi, 2017; Wang et al., 2021). The most common limitations are due to the number of channels available for the simultaneous data acquisition from some phenomenon, limited dimensions of the model due to the small scale, high costs to manufacture the model and measuring instruments, and time and work required for experimentation (Kwon et al., 2016; Moriyama et al., 2010; Moriyama et al., 2015; Yang et al., 2013). Additionally, the CFD simulation can be used to compensate for insufficient data from wind tunnels and to assist the designer in cases not addressed by the standards (Maraveas, 2020). It should also be considered that experimental evaluations do not allow to predict adverse weather conditions (Kim et al., 2019b; Uematsu and Takahashi, 2020; Wang et al., 2021).

Modeling via CFD is advantageous because it offers easiness to modify shapes and dimensions of the object and generates diverse hypotheses for the airflow. The various boundary parameters of the computational model (such as wind speed, outside and inside temperature, atmospheric pressure, air density, gravitational acceleration, viscosity coefficient, internal crop, and characteristics) have provided studies not only for structural effects, but also for ambiance in greenhouses. The CFD used to evaluate the efficiency of natural ventilation due to the height of Venlo-type multi-span greenhouses designed for tomato cultivation, contributed to the work to improve ventilation elements (Park et al., 2022).

The great challenge of CFD modeling is to accurately obtain fluctuating and peak pressures results from the wind flow complexity around the buildings, which involves a wide range of turbulence scales (Holmes, 2004). For low-rise constructions, the fluctuating effect is rather accentuated due to high turbulence close to the ground and the greatest fluctuating effect occurs in an initial part of the roof at windward as the airflow stagnates in the wall (Holmes, 2004) (Figure 6). The effects on wind pressure distribution due to aerodynamics in low and high buildings were well reproduced in CFD research (Zhao and He, 2017) with an analysis of variations in height-width and height-thickness ratios of an elliptical-shaped building. For the thickening parameters of the building profile for reference height (section at two-thirds of the building base), the authors highlighted the effects of reverse flow and sudden flow separation on the lateral faces, as well as in the windward face region with the top surface of the building. The authors also registered the effects of the sudden flow separation on the lateral faces (at two-thirds of the building base) in evaluating the building widening parameters. The results corroborate the need to consider natural wind flow fluctuations arising from surface shapes and building dimensions.

In research with turbulence models at high Reynolds numbers for high-speed trains, efforts are conducted to obtain more adaptable meshes to complex turbulent flows to improve accuracy and efficiency of flow models (Wang et al., 2017). The authors emphasize that for their purposes, rather than the LES model, less expensive computational approaches can still be obtained with the Unsteady Reynolds-Averaged Navier-Stokes (URANS), Detached Eddy Simulation (DES), and Scale-Adaptive Simulation (SAS). Due to the complexity of fluid mechanics applied to the specificities of constructions, we found studies on turbulence models proposed and experimentally evaluated in some types of greenhouses, as a summary presented in Table 2. However, accuracy of the numerical simulation results to the experimental data of a case study greatly depends on the turbulence model applied since the distribution of wind pressure is strongly influenced by phenomena arising from aerodynamics of the construction, such

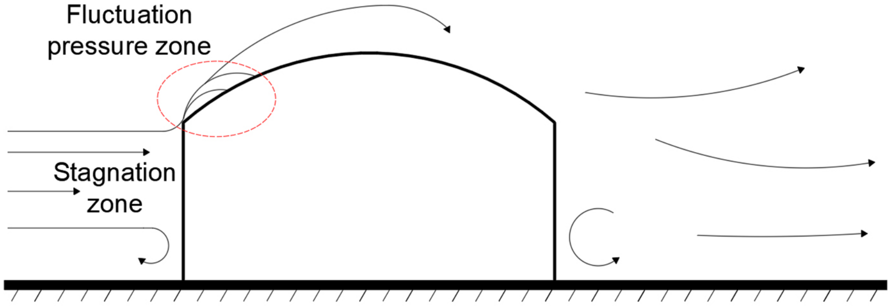

**Figure 6** – Distribution of airflow around construction detailing the zone of high fluctuation of pressure.

**Table 2** – Maximum pressure coefficients obtained by computational fluid dynamic simulations in different types of greenhouses and different turbulence models.

| Turbulence model | Greenhouse type | Maximum $c_p$* | | Main research purposes and findings | Reference |
|---|---|---|---|---|---|
| | | Overpressure | Suction | | |
| k-ε | Single span semi-circular | 0.3 | 1.3 | Good agreement between measured (real scale experiment) and predicted values of the mean pressure coefficient distribution for transverse flow and high Reynolds numbers was observed. The reason for the discrepancy between measured and predicted coefficients at the back of the greenhouse was the deformation that was not taken into account in the computational procedure. | (Mathews and Meyer, 1987) |
| k-ε | Semi-circular | 0.3 | 1.3 | Prediction of wind loads around a semi-circular considering the influence of Reynolds number and boundary layer profile. Measured and predicted coefficients were similar. Intense differences were found behind the ridge, where the full-scale shape was not exactly semi-circular. | (Mathews and Meyer, 1988) |
| k-ε | Semi-circular film-clad greenhouse | 0.3 | 1.2 | Numerical simulation to predict the distribution of wind pressure on curved greenhouses (semi-circular and semi-elliptical) and gable roof greenhouses by varying the roof angle. For the cases of semi-circular and semi-elliptical greenhouses, the pressure coefficients were similar to those observed experimentally. In the case of the multi-span greenhouse, only the first span showed a strong correlation with the experiment. The simulation results for the single-span greenhouse were more conservative than the experimental ones and the leeward face presented a good correlation with the experimental data. | (Mathews et al., 1988) |
| | Semi-circular film-clad greenhouse (more recessed into the ground) | 0.3 | 1.2 | | |
| | Semi-elliptical | 0.4 | 1.3 | | |
| | Four-span semi-circular | 0.3 | 0.9 | | |
| | Single-span glasshouse | 1.0 | 1.4 | | |
| CK | 7-span Venlo-type glasshouse | - | 1.5 | Pressure coefficients obtained by CFD in the roof of a Venlo-type greenhouse compared to the experimental data. The CK (Chen and Kim) model was used, which is a modification of the model of the standard k-ε. The authors found a good agreement between experimental and numerical data along the first three spans. Numerical results have shown the minimum of the suction force almost at the middle portion of the windward slopes, while experimental data show the minimum of the suction force at the windward side of every span roof near the ridge. | (Mistriotis et al., 1997) |
| k-ε | Multi-span Venlo-type glasshouse | - | 1.1 | CFD simulation of the pressure coefficients in a Venlo-type greenhouse using the standard k-ε and RNG k-ε turbulence models, with models validated by literature data. The main differences between the experimental and simulation results were verified in the first span. The authors concluded that the RNG k-ε turbulence model presented a better correlation with the experimental results. | (Reichrath and Davies, 2002) |
| RNG k-ε | | - | 0.9 | | |
| k-ε | Semi-cylindrical tunnel greenhouse with two symmetrical openings | 1.1 | 1.7 | Determination of the external and internal pressure coefficients in a tunnel-type greenhouse with various configurations of openings, in which discrepancies were found between the calculated coefficients and those recommended by European standards. | (Mistriotis and Briassoulis, 2002) |
| | Semi-cylindrical tunnel greenhouse with one opening at the leeward side | 0.9 | 1.8 | | |
| DNS | Two-span Parabolic roof | 0.2 | 0.8 | Determination of external pressure coefficients in greenhouses with parabolic roofs arranged in tandem. The distribution of $c_p$ was different over the two greenhouses, in which the first span obtained $c_p$ values close to those established by Eurocode (CEN, 2001), while the second span presented different values. | (Ntinas et al., 2017) |
| Standard k-ε | Three-span Venlo-peach-type ventilated greenhouse | 0.8 | 1.1 | Comparing the results of simulation and experimentation in a wind tunnel (Kwon et al., 2016), for $c_p$, the correlation coefficient was equal to 0.99. Furthermore, the $c_p$ values found were like those established by EN 1991-1-4 (CEN, 2005). | (Hur and Kwon, 2017) |
| Standard k-ε | Three-span arch type | 0.7 | 1.4 | Combination of the permanent and wind actions modeled via CFD to evaluate the distribution of stresses in the structure. Good correlation between simulation and experimental data (correlation coefficient equal to 0.99). | (Hur et al., 2018) |
| LES | Pitched roof: even-span | 1.9 | 1.9 | Prediction of pressure coefficients using the LES turbulence model and validation with wind tunnel experimentation. The results obtained were closer to the experimental ones using LES when compared to the use of the RANS turbulence model. | (Kim et al., 2019b) |
| | Pitched roof: mono-span | 1.8 | 1.4 | | |
| | Pitched roof: three-quarter type greenhouses | 1.5 | 1.0 | | |
| | Vaulted roof: arch | 1.8 | 3.5 | | |
| | Vaulted roof: peach | 1.5 | 3.0 | | |
| | Vaulted roof: wide-broad type greenhouses | 1.2 | 2.9 | | |

Continue...

**Table 2** – Continuation.

| | | | | | |
|---|---|---|---|---|---|
| k-ε | Arc-shaped greenhouse height/span ratio = 0.3 | 0.8 | 0.85 | Evaluation of pressure coefficients in an arch-shaped greenhouse with a deformed structure using different turbulence models and different height/span ratios. The deformed shape did not influence either the distribution of $c_p$ in the wall zone or the position of $c_p$ inversion. | (Vieira Neto and Soriano, 2020) |
| k-ω | | 0.95 | 1.0 | | |
| k-ε RNG | | 0.9 | 0.9 | | |
| k-ε | Arc-shaped greenhouse height/span ratio = 0.6 | 0.85 | 0.85 | | |
| k-ω | | 0.9 | 0.85 | | |
| k-ε RNG | | 0.85 | 0.8 | | |
| k-ω SST | Multi-span arc-shaped greenhouse | 0.4 | 1.2 | Determination of pressure coefficients in greenhouses with multiple spans and discussions about discrepancies with the results given by the European standard. | (Fernández-Garcia et al., 2020) |
| Realizable k-ε | Single span Peach type greenhouse | 0.6 | 1.0 | Evaluation of the distribution of the mean pressure coefficients using the RANS turbulence model and investigation of structural reinforcements to improve wind resistance. Considering the FSI effect, the simulated collapse mode corresponded well to observations in damage investigations. | (Uematsu and Takahashi, 2020) |

$c_p$ = pressure coefficient; k-ε = k-epsilon model; k-ω = k-omega model; CFD = Computational Fluid Dynamic; RANS = Reynolds Averaged Navier-Stokes; RNG = Renormalization Group; DNS = Direct Numerical Simulation; LES = Large Eddy Simulation; SST = Shear Stress Transport; FSI = Fluid-Structure Interaction; *The pressure coefficients obtained from graphical representations of the original articles are approximate values.

as stagnation and fluid separation, reconnection, and vortex (Meng et al., 2018). Since there is no universal turbulent model (Králik et al., 2017), validation of computational methods is necessary, as demonstrated by the numerous studies that have tested and compared the results of variations in wind flow related to the characteristics of the building and its surroundings.

The SAS turbulence model was developed from the URANS model, in which SAS stands out as a difference in its capacity to solve part of the turbulence spectrum for unsteady flows due to spatial and temporal scales. In contrast, the URANS model can only include vortex shedding at large scales. The authors further reported that innovation of this turbulence model is due to the von Karman length scale introduced to cover adaptive temporal and spatial scales. Mathematically, the SAS model resembles the RANS approaches and the subscale model using LES (Wang et al., 2017). The better performance of the SAS model compared to the URANS calculation is related to the accurate reproduction of unsteady fluctuations around the building (Jadidi et al., 2018).

The SAS model is more attractive than the Embedded Large Eddy Simulation (ELES) model due to the considerably lower computational cost, as half the processing time was used to the pressure drag coefficients in the case studies (Maleki et al., 2017). In a systematic study, comparing computational modeling and wind tunnel models, the SAS model was suggested as a reasonable alternative to Improved-Delayed-DES (IDDES), as similar high accuracies were achieved at a lower computational cost (Wang et al., 2017).

In the evaluation of various types of multi-span greenhouses using the Shear Stress Transport turbulence model (SST k-ω), the mesh size was defined by the independence test and computational domain (Kim et al., 2017). The SST k-ω turbulence model was used to evaluate the external pressure coefficients in greenhouses of multiple spans (Fernández-Garcia et al., 2020), which detected values different from those presented by EN 13031-1 (CEN, 2001) from the first to the third archs. However, these results followed the coefficients of EN 1991-1-4 (CEN, 2005), which addresses the wind action in general constructions. In the second roof of parabolic greenhouses arranged in tandem, the difference between the values of the coefficients obtained by the simulation and those prescribed by EN 13031 (CEN, 2001) was related by Ntinas et al. (2017). These differences reinforce the need to develop scientific research on vicinity effects (Moriyama et al., 2010; Wang et al., 2021).

Remarkably close and slightly divergent values were obtained for mean and peak pressure coefficients, respectively, with the LES turbulence model applied in the simulation of greenhouse and the wind tunnel analysis (Kim et al., 2019b). The authors also compared these results with the values obtained using the RANS turbulence model detailed in Kim et al. (2017). They concluded that the LES model was more accurate to determine the mean coefficients of wind pressure.

The DES model has been identified as better than the RANS and LES models (Sharma et al., 2019). DES is a hybrid of the URANS and LES models and applies the URANS mode to the attached contour layers, while the LES mode is applied to the detached regions. Therefore, for cases of flow around the bluff-body, which cause high turbulence, as in the case of wall-to-roof encounters, the DES requires fewer points and a lower computational cost than the LES model.

In the group of models defined as Scale-Resolving Simulation (SRS), there is also the SAS mode that operates with the second derivative of the velocity within the length scale equation, without affecting the RANS behavior (Menter and Egorov, 2010). The need to apply an SRS method in external and detached zones is due to the limitations of RANS to simulate such zones

(Pereira et al., 2021). Using the SAS model to simulate fluid flows separated from curved surfaces, the adapted model could better represent the turbulence zones in relation to the elliptic blending RANS model (Yang and Yang, 2022). Therefore, the SAS model was more accurate to predict the results of the experimental pressure coefficients.

The fatigue effect on Venlo-peach-type greenhouse structures was evaluated using the advantages of computational simulation in the simultaneous consideration of self-weight actions and wind with speeds equal to 6 and 30 m $s^{-1}$ (Hur and Kwon, 2017). From the simultaneity of these actions, the authors concluded that the fatigue effect was reduced due to the action of self-weight and the life cycle of the structure was increased by 21 %. However, this effect decreases with wind speed increases and the quantification for the stress analysis was proposed in a model normalized by the wind speed square (Hur and Kwon, 2017). With the model established, the CFD simulation results were compared with the experimental results of Kwon et al. (2016), resulting in a correlation coefficient of 0.99. In that same study, the pressure coefficients obtained in the simulation were compared with the values of EN 1991-1-4 (CEN, 2005) and Korean standards, showing that the results were closer to the pressure coefficients established by European standardization.

Studies of deformations in plastic-coated greenhouse structures have been performed, given their importance to greenhouses' design and structural safety (Jiang et al., 2021; Ren et al., 2019). To evaluate the deformation effects on the pressure coefficients, in the CFD simulation of arched roof greenhouses as a perfectly rigid solid, the non-displaced structure and deformed structure (Figure 7) were adopted according to the limits allowed by CEN (2001). Differences were more pronounced along the arch extension due to reduced pressure coefficients in the region near the ridge (Vieira Neto and Soriano, 2020). The windward roof region, where there is a high fluctuation of pressure (Figure 6), showed an inversion of pressure coefficients (from overpressure to suction). This occurrence is corroborated by the analysis conducted in a wind tunnel test by Yang et al. (2013) for greenhouses covered with plastic film. This inversion effect of the pressure coefficient is related to the height/span ratio of the greenhouse, which is not addressed by EN 13031-1 (CEN, 2019).

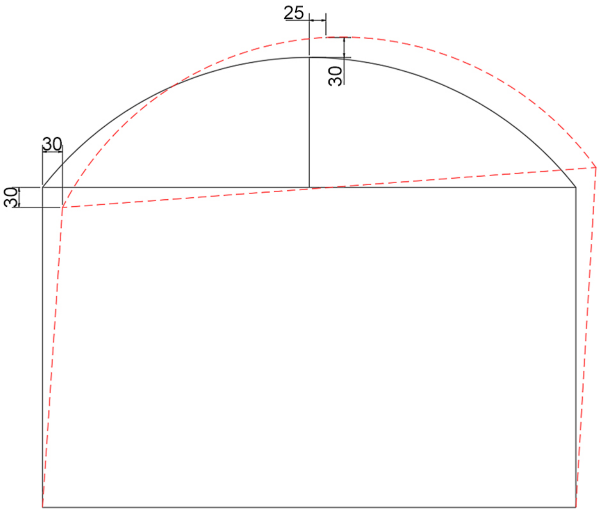

**Figure 7** – Front view of the displaced arched roof greenhouse (dashed lines) for CFD modeling. Dimensions in mm.

Suction is highlighted as one of the leading causes of plastic film rupture, an incipient phenomenon due to the lack of standards and scientific studies on the design of plastic film fixation systems in the greenhouse structure. The suctioned plastic film behaves like a balloon and causes overload in the fixation system along the perimeter of the structure (Dougka and Briassoulis, 2020). This phenomenon studied in the field of computational modeling shows the relevance of the interaction effects of plastic coating with the greenhouse structure and confirms the behavior of plastic film already addressed in the experimental studies discussed in this study.

Most studies conducted to obtain the external coefficients of wind pressure in greenhouse structures, either experimentally or computationally, consider the mean pressure coefficients (time-averaged). Distribution of the pressure coefficients changes with the displacement of the structure, which implies the need to consider the fluid-structure effect since the results found without this consideration are different from reality (Uematsu and Takahashi, 2020). Studies are expected to investigate further the use of computational models with these approaches to improve data accuracy required for project safety in terms of structure and coating of greenhouses.

## Final Remarks

In this study, the main advances achieved in methods to obtain wind aerodynamic coefficients were thoroughly investigated, which should be applied in the structural analysis of greenhouses. A striking feature of greenhouses, compared to the usual rural constructions, consists of the coating material used to meet the requirements of protection and interaction between crop and solar energy, where plastic film is the most common material for covering greenhouses, mainly in tropical regions. However, due to its high flexibility, this low-cost and easy-to-apply material exhibits behavior that has generated discussions about the accuracy of wind pressure coefficients in the greenhouse structure. The values of pressure coefficients can be obtained from specific standardization for greenhouses, by experimental methodologies of prototypes (in the field or a wind tunnel), and by fluid-dynamic computational methods.

However, they are distinct means that, in some cases, can even complement each other but individually or together have their limitations. Therefore, the issue involving accuracy of pressure coefficients for plastic-covered greenhouses has yet to be exhausted.

The literature on the use of plastic film has shown that the values of essential pressure coefficients for structural design can present relevant differences depending on the methodology used. Regarding the pressure coefficients obtained from standardizations for wind actions and greenhouses, we highlight the limitations for the shapes of the construction. Since the standards do not cover all the usual types, there is a lack of data on the coefficients related to the aerodynamics of the construction. Special attention should also be given to the effects on greenhouses built with large extensions, as well as the neighborhood effects arising from other constructions or natural barriers. For the covering materials, in relation to glass, whose surface is stable, it is questioned how much the plastic film's flexibility can modify the aerodynamic coefficients' values. The surface of the plastic film covering is unstable to wind action and the instantaneous change in the surface shape must imply changes in the airflow, mainly in the parts with vortices formed next to the covering surface. The instantaneous effects of wind action are a source of attention by some researchers, as well as by EN 13031-1, which presents a model for combinations of actions for the use of plastic film in tunnels, taking into account an increase in overpressure on the windward side because the plastic film is tensile by the leeward suction. This covering-structure interaction mechanism requires further studies, as its effects may result in the instability of parts of the structure.

Experimental techniques with full-scale tests can be limited mainly to control wind characteristics, such as intensity and flow direction. Additionally, time and financial investments required to build the prototype are essential factors that may restrict experimental conditions. The demand for resources must also be planned when there is a need to modify the prototype and the surrounding conditions. Tests with small-scale models carried out in a wind tunnel provide data for the analysis of pressure distributions in different construction cases and are also highly recommended for cases of projects not contemplated by specific standards for wind actions. Depending on the complexity of the construction, mainly shape and dimension, many devices for data acquisition may be necessary and special care must be taken with the representative scale of the models to be tested.

The CFD simulation tool has provided a great technological advance to evaluate wind effects in civil construction due to the possibilities of quick modifications and implementation of variables that affect the behavior of air flowing through modeled objects, in this case, the construction. Based on a mathematical model to represent airflow by the laws of fluid dynamics, the spatial discretization by volume elements requires a mesh whose intensity must be adequate for accuracy of the results. In studies using CFD modeling of greenhouses, pure turbulence models based on RANS were used, which are well suited to the flow of fluid attached to a surface or even on the LES model to represent the fluid detached from the surfaces of the construction. Implementing the DES hybrid model, which adapts the mesh to the areas of flow detachment, increased accuracy of the results.

The literature has shown in research on simulations of objects with bluff-body and/or develop high variations in the air velocity gradient, a certain viability of using SRS methods, due to the adjustment of the model with turbulence scale variable with time. However, for the simulations of agricultural greenhouses, we noticed a lack of these hybrid methods that adjust the turbulence scale as a function of time to allow the abrupt changes in the airflow around the buildings to be coherently represented. This lack of methods is also noted in research on plastic film detachment from the structure of greenhouses due to the wind flow, which modifies the covering surface in an instantaneous and unstable way, altering the distribution of aerodynamic coefficients in the construction. Therefore, the SAS model can be an alternative for studies of wind flow on covering plastic films. Further research on model searches is needed to adjustment of the fluid-structure behavior of greenhouses better.

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## Authors' Contributions

**Conceptualization:** Soriano J, Shiguemoto ACG. **Data curation:** Soriano J, Shiguemoto ACG, Vieira Neto JG. **Formal analysis:** Soriano J, Shiguemoto ACG, Vieira Neto JG. **Investigation:** Soriano J, Shiguemoto ACG, Vieira Neto JG. **Methodology:** Soriano J, Shiguemoto ACG, Vieira Neto JG. **Project administration:** Soriano J. **Supervision:** Soriano J. **Writing-original draft:** Soriano J, Shiguemoto ACG, Vieira Neto JG. **Writing-review & editing:** Soriano J, Shiguemoto ACG, Vieira Neto JG.

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