Review of experimental and theoretical techniques applied to the study of wind in vegetative canopies (2019-2023)

RODOLFO DEMATTE[1,2], ERNESTO GANDOLFO RASO[1], JOSEFINA HUESPE[1]
[1] Universidad Tecnológica Nacional
Facultad Regional Mendoza
Coronel Rodríguez 273, Ciudad – Capital
(M5500) Mendoza
ARGENTINA

Abstract: - In this study, a systematic review spanning the last 5 years (2019-2023) was conducted to explore both experimental and theoretical techniques utilized in examining wind dynamics within vegetative canopies. A comprehensive search was carried out across academic repositories ScienceDirect® and Google Scholar®, employing specific keywords pertaining to wind studies in agricultural contexts. The search scope was confined to the period between 2019 and 2023 to encompass the most recent advancements in the field. The findings obtained not only showcase the advancements made in this domain but also unveil unexplored avenues for future research. Additionally, the review highlights emerging techniques that are still in their nascent stages. Despite the significant progress witnessed over the past five years, there exists a need for sustained investigation into this topic, with potential expansions into alternative research perspectives proposed within this study. Further exploration into the influence of canopy porosity and varietal composition on the efficacy of windbreak structures remains crucial, given the continued relevance of windbreaks in mitigating wind-induced stresses in agricultural settings.

Key-Words: wind – vegetative canopies – windbreakers- wind tunnel -CFD - crops

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1 Introduction

Wind can significantly influence crop canopies. Among its positive aspects, wind aids in pollen and seed transport, regulates crop temperature, facilitates gas diffusion, and enhances plant mechanical resistance as an adaptive response [1]. However, wind also has negative impacts on plants depending on wind speed, including desiccation, physical damage, disease dispersion, loss of flowering, fruit drop, as well as affecting the surrounding environment through wind erosion and soil nutrient loss [2]. Additionally, wind action mobilizes soil particles that remain suspended in the air [3], affecting human health through prolonged exposure [4]. While some research focuses solely on the effect of wind on crops [4] [5], this methodology also applies to analyzing dispersion phenomena in agrochemical applications and evaluating soil erosion [3] [4]. Furthermore, various studies concentrate on analyzing wind incidence on windbreaks, which have long been used to mitigate adverse wind effects [6].

As a starting point, a review titled "Turbulent Flow in Plant Canopies: Historical Perspective and Overview" [7] was analyzed, providing an ex post facto historical analysis of turbulent flow study in plant canopies and groves. This historical review spans a period of 50 years (1970-2020), evaluating different variants of studying wind behavior on vegetative crops, with a focus on crops with homogeneous canopies. It details a timeline [7] classifying different stages of wind study in crops:

1) From the 1980s to 2000, there was significant development in methodologies for analyzing wind behavior in crops, emphasizing in situ measurements and wind tunnel usage, techniques that have enriched experimental knowledge [7].
2) Between 2000 and 2020, methods for turbulent flow measurement improved, further clarifying plant physiological behavior with the environment,

assessing changes in different geometries and spatial distributions. Concurrently, various Computational Fluid Dynamics (CFD) software emerged, including the open-source program openFOAM®, accessible and modifiable by the user community [7].

Currently, wind tunnel testing is the most widely used experimental technique for studying wind flow in vegetation, validated with CFD simulations [8] [9] [10]. Some studies reverse this, modeling in CFD and validating data with wind tunnels [8]. Others use wind tunnels and field tests to study wind forces on crops [9] [10]. Authors highlight wind tunnels' superiority over field experiments due to their controllability [11]. Much research has been conducted on the topic, but information is scattered. Therefore, this Review arises from the need to synthesize knowledge generated in the last 5 years. Building on research [7], this Review aims to evaluate the current state of research on methods for assessing wind impact on crops from 2019 to 2023.

2 Material and Methods

2.1 Search and Article Selection

An exhaustive review of scientific literature was conducted using two repositories and academic databases, including ScienceDirect® and Google Scholar®. Specific keywords related to wind study in crops were used, including "wind tunnel," "CFD," "windbreakers," "crops," and "canopy." The search was limited to the period between 2019 and 2023 to ensure inclusion of the most recent studies.

2.2 Inclusion and Exclusion Criteria

Selected articles were assessed based on predefined criteria. Studies specifically addressing wind study in crops using techniques such as wind tunnels, Computational Fluid Dynamics (CFD), and/or windbreak effectiveness evaluations were included. Articles not available in full text and those not directly addressing the topic of interest were excluded. Only 34 articles passed this stage.

2.3 Article Analysis

Each article was carefully reviewed to extract relevant information on techniques used in wind study in crops. Details on experimental design, wind measurement methods (including wind tunnels and/or CFD simulations), characteristics of crops studied, and results related to crops or windbreak effectiveness were recorded.

2.4 Results Synthesis

Key findings of each article were summarized and analyzed, focusing on methods used to study wind in crops and its impact on canopies. Emerging trends, research gaps, and areas of interest for future studies in the field were identified.

3 Problem Solution

According to the results analyzed in the literature reviewed in this review, a temporal evolution from 2019 to 2023 can be observed, in which numerical simulation techniques become important by comparing data with experimental techniques. Table 1 provides a summary of articles evaluated in this review, classified by author, year of publication, theme addressed, experimentation method, and validation method used. From these data, articles were classified based on the methods used for wind impact analysis and their application to the study of wind influence on crops, focusing on the characteristics of tree canopy structure, studies related to plant variety, and its physical and morphological characteristics. Additionally, various researches aimed at mitigating the harmful effects of wind and evaluating wind drag coefficients in plantations and objects were analyzed. Upon concluding the review, the current landscape of advancements in wind behavior research in crops and other related studies is surveyed.

3.1 Techniques Used for the Study of Wind Impact on Crops

In the analysis of the articles evaluated in this review (Table 1), wind tunnel and CFD simulations are the main methodologies for assessing wind behavior in crops. Other studies [12] [13] reveal the use of machine learning as a new technique for evaluating the phenomenon.

3.1.1 Wind Tunnel

Since its creation in the 19th century, wind tunnel has been used as a tool to evaluate wind behavior to understand dynamic interactions between fluids and solid objects [14]. A wind tunnel is a device to produce a controlled air stream to study the effects of moving air or air resistance on models of aircraft and other machines and objects [15]. Other authors [16] [9] comment that the wind tunnel is a continuous subject of tests and trials since the position of the model in the wind tunnel test area influences the experiments. Despite this, it is highlighted that the wind tunnel is one of the most reliable tests [16]. In agriculture, the use of wind tunnels is a very useful tool, from the study of precision agriculture, aerial application of fertilizers and poisons, wind effects on crops and flowering, wind erosion of soils, among other uses [15].

Table 1: Summary of Evaluated Articles

Authors	Topic of the evaluated article	Method used	Year	Analyzed object	Contrast method used
Gonzales, *et al.*	Drag coefficients	CFD openFOAM	2019	Vegetation canopy	Empirical models
Philips, *et al.*	Wind flow dynamics	Review	2019	Buildings and crops	Comparatives studies
Cheng, *et al.*	Wind flow dynamics	Wind-tunnel	2019	Vegetation canopy	Experimental dataset
Shnapp, *et al.*	Lagrangian wind flow dynamics	Real-time image analysis system	2019	Vegetation canopy	Wind tunnel experiment
Zhu, *et al.*	Manufacturing technology models	CFD openFOAM	2019	Objects	Wind tunnel experiment
Hesp, *et al.*	Wind flow dynamics	Wind-tunnel	2019	Vegetation canopy	Experimental dataset
Gonçalves, *et al.*	Drag coefficients	Review	2020	Vegetation canopy	Comparatives studies
Gough, *et al.*	Wind pressure	Wind-tunnel	2020	Buildings	openFOAM
Ismail, *et al.*	Wind turbulence models	CFD openFOAM	2020	Turbulence models	Wind tunnel experiment
Kim, *et al.*	Wind flow dynamics	CFD openFOAM	2020	Greenhouses	HNVR-SYS
Sherman, *et al.*	Wind flow dynamics	Review	2020	Objects	Comparatives studies
Kucera, *et al.*	Wind erosion	Optical porosity in windbreakers	2020	Vegetation canopy	Empirical models
Makedonas, *et al.*	Wind flow dynamics	Wind-tunnel	2020	Vegetation canopy	Experimental dataset
Qin, *et al.*	Wind flow dynamics in seeds	Wind-tunnel	2020	Vegetation canopy	Experimental dataset
Zhang	Wind pressure	Wind-tunnel	2020	Buildings	Experimental dataset
Brunet	Wind flow dynamics	Review	2020	Vegetation canopy	Comparatives studies
Guo, *et al.*	Vegetative windbreaks	CFD openFOAM	2021	Vegetation canopy	Wind tunnel experiment
Gardiner, *et al.*	Wind flow dynamics	Review	2021	Vegetation canopy	Comparatives studies
H'ng, *et al.*	Wind flow dynamics	Wind-tunnel	2022	Vegetation canopy	Empirical models
Ismail, *et al.*	Design wind tunnel	Wind-tunnel	2022	Wind tunnel	Wind tunnel experiment
Mo, *et al.*	Drag coefficient	Wind-tunnel	2022	Vegetation canopy	Wind tunnel experiment
Qin, *et al.*	Wind flow dynamics in seeds	Wind-tunnel	2022	Vegetation canopy	Experimental dataset
Scagnellato, *et al.*	Spraying in canopy	Algorithm	2022	Vegetation canopy	Simulations
An, *et al.*	Permeability windbreak	Wind tunnel experiment	2022	Vegetation canopy	Phonics software
Torkelson, *et al.*	Wind flow dynamics	Wind-tunnel	2022	Vegetation canopy	Experimental dataset
Yan, *et al.*	Wind flow dynamics	Wind-tunnel	2022	Vegetation canopy	Empirical models
Cintolesi, *et al.*	Wind flow dynamics	CFD openFOAM	2023	Isolated forest	Experimental dataset
Chockalingam, *et al.*	Wind profiles in objects	CFD openFOAM	2023	Objects	Machine learning
BenMoshe, *et al.*	Wind flow dynamics	Machine learning	2023	Buildings	Comparatives studies
Ru, *et al.*	Permeability windbreak - spraying	Wind-tunnel	2023	Vegetation canopy	Experimental dataset
Ulmer, *et al.*	Wind flow dynamics	Quic simulation-winds	2023	Vegetation canopy	Empirical models
Casa L. *et al.*	Design wind tunnel	Ansys	2023	Objects	Wind tunnel experiment
Renault, *et al.*	Wind flow dynamics	Quic canopy model	2024	Vegetation canopy	Model WRF
Wang, *et al.*	Windbreak effectiveness	CFD	2024	Vegetation canopy	Wind tunnel experiment

The use of wind tunnels is an important experimental technique for the study of velocity distribution patterns, pressure study, and fluid turbulence intensity. In wind tunnels, tests can be carried out at different speeds with different turbulence models: k-epsilon, the k-omega model, the RSM model, the SST k-omega model, and the Large Eddy Simulation (LES) model [18] [19].

• K-epsilon Model: This is one of the most used turbulence models and establishes equations for turbulent kinetic energy (k) and the dissipation of this energy (ε). It is widely applicable and relatively easy to use.

• K-omega Model: This model also focuses on turbulent kinetic energy but uses an additional variable (ω) to describe the turbulence rotation rate. It is particularly useful in flows of high turbulence intensity.

• SST k-omega Model: This is a combination of the k-omega model and the k-epsilon model, which provides greater accuracy in a variety of flows, especially in the boundary layer. Equation models like k-epsilon and its derivatives are intuitively easy to understand and are relatively stable mathematically; however, these turbulence closures cannot address complex flows that include flow separation, vortex zones, or recirculation, nor abrupt changes in geometry [19].

• RSM Model (Reynolds Stress Model): This is a more advanced approach that directly models the components of the Reynolds stress tensor. It is more accurate in complex flows but also more computationally expensive.

• LES Model (Large Eddy Simulation): Unlike the previous models, LES directly resolves the larger scales of turbulence, while the smaller scales are either modeled or sub-sampled. It is highly accurate but also computationally demanding and is mainly used in numerical simulations rather than in wind tunnels.

This is one of the reasons why LES seems to work better for flows around buildings than RANS. An LES formulation directly solves the flow for the largest eddies and simplifies the treatment of the smaller ones (less than 10 centimeters) [19].

Due to the high cost of wind tunnels, some authors [16] propose the design of a low-cost open-circuit subsonic wind tunnel for aerodynamic measurement and characterization, as a laboratory equipment for physical property measurement [16] [20]. Another aspect to consider in wind tunnel experiments is the assembly of test models; various materials are used in their elaboration, in some cases, they are made with live plants, and in other cases, due to issues associated with the size of the wind tunnel, scale models that mimic crops are designed [4]. The use of 3D additive manufacturing technology is highlighted in the creation of prototypes and models [15], as it represents an advance in the manufacture of representative scale models, with advantages such as low manufacturing costs, ease of assembly, and reduction of the number of parts to be assembled [17].

3.1.2 Computational Fluid Dynamics (CFD)

In the case of CFD simulations, the SIMPLE algorithm (Semi-Implicit Method for Pressure-Linked Equations) based on RANS (Reynolds-averaged Navier–Stokes equation) is used [21], as it presents itself as an economical alternative compared to computational expenditure compared to other specific turbulence models, for example, LES [22].

The computational fluid dynamics method is applicable with different mathematical modeling for turbulent flow studies although depending on the model, it requires substantial computational power to simulate it accurately [16]. In the study of wind behavior in vegetative canopies, both wind tunnel tests and CFD simulations have produced coincident results [23] [24]. Numerical simulation is indispensable for research; it is deduced that both methods are complementary, although some authors argue that CFD could replace some wind tunnel tests [9] [19].

3.1.3 New Proposed Techniques

In recent years, the use of machine learning has emerged as a new technique for evaluating wind behavior in crops. Machine learning algorithms use data from CFD and wind tunnel to predict wind behavior [12] [13] presents itself as a variant to CFD since computational calculation becomes very costly and time-consuming when performing computer simulations. [8] uses Artificial Neural Networks (ANN) and other authors the k-Nearest Neighbors algorithm (k-NN) [12] are techniques used in the field of machine learning. Both are approaches that fall within the category of supervised learning, where labeled data are used to train models and make predictions. In the case of Artificial Neural Networks, it is a more advanced approach that involves constructing a network architecture with interconnected nodes, and the weights of those connections are adjusted during training so that the network can learn to perform specific tasks. In contrast, the k-Nearest Neighbors algorithm is a simpler technique where predictions are based on the majority of class labels of the K nearest neighbors in the feature space.

The K-nearest neighbors (kNN) method [12] allows classification, and by using regression, it enables predicting and inferring the phenomenon. In parallel, RANS simulations were performed, which require many calculations, provide quite accurate results to understand flow patterns in urban areas and data obtained from wind tunnel measurements. These data allow the algorithm to learn automatically and can predict the phenomenon; thus, computational challenges associated with modeling were addressed. The results obtained demonstrate that convergence time is reduced by 50%. Regarding simulations both in wind tunnel and in OpenFoam, predictions obtained through machine learning are consistent with data obtained in wind tunnel as well as CFD simulations.

As an advantage, the use of machine learning is a less complex alternative to performing a Navier-Stokes simulation (RANS) in a CFD program. The tests carried out allowed characterizing horizontally averaged wind and temperature profiles within the urban canopy using machine learning techniques, comparing the data with the results of the CFD simulation applying the SIMPLE algorithm of openFOAM

3.2 Analysis Approach Classification of Studied Works based on Particle Trajectory Study

3.2.1 Based on Particle Trajectories

Generally, wind study approaches rely on Eulerian studies, where fluid movement is analyzed at fixed points evaluating different parameters within the canopy [1] [4] [8] [13] [21] [22] [23]. Alternatively, the Lagrangian perspective proposes studying wind behavior and turbulence in vineyards, tracking particle trajectories [24]. A detailed analysis of velocity distribution in wind tunnels validated with CFD is conducted in this study. Successful measurements of Lagrangian particle trajectories within a modeled canopy layer in a large-scale environmental wind tunnel yield results representing turbulent Lagrangian flow in the homogeneous canopy model [24].

3.2.2 Based on Canopy Structure Characteristics

Wind's direct and indirect influence in agriculture leads to wind studies in crops being divided based on canopy or plant cover. Canopies can be homogeneous, dominated by organized monoculture in rows, or heterogeneous, with diverse varieties, sizes, and configurations.

3.2.2.1 Studies in Homogeneous Canopies

Modern agricultural production's high level of technification organizes crop systems to maximize yield and space while facilitating standardization processes. Many crops are organized in homogeneously arranged plots or rows, promoting better plant aeration and uniform agricultural management practices (harvesting, pruning, and spraying). The homogeneous canopy model assumes uniform vegetation in terms of height and density [8] [22]. For instance, recent years have seen the design, evaluation, and comparison of new CFD software for vineyards. This software models wind behavior within the crop, considering flows, wake formation, pressure-influenced zones, and adjusts roughness near the canopy's leading edge. Results, validated against wind tunnel tests and field experiments, represent a first step towards developing a comprehensive rapid-response environment for simulating scalar transport in row-organized homogeneous canopies [22].

In a homogeneous canopy, wind flow behavior can be divided into different vertical regions from the ground surface to the canopy top, characterized by low-speed fluids, intermittent but complex turbulence, and vertical gradients due to wind movement. This includes a roughness layer, a sub-roughness layer, and a transition region above the canopy where fluid is influenced by different wind directions, along with an atmospheric surface layer where fluid velocity generally follows the Monin-Obukhov similarity theory [22]. Furthermore, erosion mechanics and the effect of standing vegetation were evaluated, with simulations and wind tunnel validations showing effective drag coefficients with no significant differences between experimental and simulated results [25].

3.2.2.2 Studies in Heterogeneous Canopies

The heterogeneous canopy model approximates crop geometry, where configuration and species variety aren't uniform, allowing for simulations closer to reality. One study evaluated the effect of vineyard canopy heterogeneity on wind speed, transport processes, and generated turbulence [11]. Another study focused on wind flow and turbulence evaluation in a natural forested area with heterogeneous forest cover, identifying different vertical wind movement layers and horizontal flow regions within the non-homogeneous canopy [26].

3.2.3 Studies Related to Variety, Physical, and Morphological Characteristics

Considerations for forest curtain configurations include variety, plant type, dimensions, and canopy porosity. Various studies indicate that element distribution is related to wind attenuation in dense vegetation environments and recirculations near element channels [1] [21]. Variety selection is crucial for forest curtain design due to morphological aspects associated with selected plant dimensions. Variety and plant type determine canopy density levels, correlating with canopy porosity. Canopy porosity analysis and its impact are essential, often determined through wind-facing crop surface photography to ascertain optical porosity [27].

New methods involve mobile laser scanning systems in wind tunnels to evaluate velocity variations, showing higher validation degrees [28]. Results demonstrate rapid wind velocity reduction upon canopy penetration, with lower optical porosity correlating with greater wind speed reduction [28].

3.2.4 Studies Aimed at Mitigating Wind's Harmful Effects

Windbreak usage, an ancient mitigation method, is a focus of recent research, evaluating their arrangement, dimensions, and efficiency. Large vegetal structures act as barriers for turbulent flows, dissipating particles and wind momentum within a canopy [29]. They also prevent wind erosion within crop fields [27]. Windbreak effectiveness and wind behavior evaluation are crucially influenced by plant species in forest barrier design and efficiency.

3.2.5 Evaluation of Drag Coefficients

Drag resistance calculation is another analysis variable, with various authors studying drag coefficients. Some conduct detailed historical studies comparing urban tree drag coefficients across years [10]. Others evaluate wind flow over different idealized vegetation canopy configurations, proposing new analytical solutions for wind velocity over vegetation canopies, validated successfully in wind tunnel experiments [32].

3.2.6 Advancements in Wind Behavior Studies

Recent advancements include rapid modeling using QUIC software, resolving complex wind fields and simplifying roughness impact, particularly applicable in situations requiring swift intervention such as fire risk management or disease spread [21]. New models describing wind behavior and air velocity distribution around individual plants have been developed [31]. Future research will focus on tree height and shape, studying shelter effects, and evaluating windbreak systems in wind erosion-prone areas, considering optical porosity and windbreak height.

3.2.7 Other Studies of Interest

Wind studies extend to environmental factors' effects like wind erosion, seed dispersal, pest control, and fertilization techniques, akin to studies on wind incidence on structures or obstacles. Seed dispersal by forest curtains due to increased wind flows is another area of interest [35]. Forest curtains also retain seeds from other crops carried by the wind, with studies analyzing seed retention influenced by curtain height and porosity [36]. Moreover, computational algorithms predict fertilizer and agrochemical spraying patterns based on wind direction in vineyards [37]. In greenhouse studies, precise wind behavior analyses are conducted due to controlled environmental conditions, evaluating temperature variations and wind behavior [38]. Wind studies on obstacles draw on building and structure studies, systematically comparing wind angles' incidence on both idealized and real urban structures [39]. These studies may have applicability in agriculture for wind behavior analysis in crops.

3.2.8 Highlights

In summary, from the articles selected for this review, the following results can be highlighted:

- The effectiveness of windbreak curtains is associated with their design and proper functioning [23].
- It depends on tree density and porosity [23].
- The flow displaced between trees decreases as porosity reduces [23][32].
- The ideal distance between the windbreak curtain and the crop is where wind is reduced by 20% [23].
- Results indicate that the minimum distance between the windbreak curtain and the protected crop must be greater than 5 times the height for curtains of 1 meter height [23].
- The minimum distance is inversely proportional to windbreak density [23].
- Some authors suggest that the optimal spacing distance between rows for bushes should be 1 to 3 times the height of the bush, with an optimal number of three rows [8].
- A relationship was found between canopy width and velocity distribution in the plane [31].

- Windbreak barriers improve effectiveness when having a second row [23].
- Double-row windbreaks are suitable for low speeds, while two-row with one belt and three-row with one belt windbreaks are optimal for medium and high speeds, respectively [8].
- Results demonstrate that large-scale movements increase, as do turbulent transport processes in tests with vegetation canopy models configured in staggered and aligned patterns with different vegetation densities [32].
- The optimal arrangement of plants is staggered, and specific bush windbreaks are optimal for speed reduction [8].
- The protected area by forest curtains is proportional to their height [33].
- Results show that the shelter effect of forest curtains increases as canopy width increases, with this effect observed to a lesser extent concerning length [29].

4 Conclusion

A compilation of the evolution of wind impact studies on crops is presented here, focusing on transport processes and crop aerodynamic resistance. Additionally, new perspectives on wind studies that are underexplored or not considered in previous research are offered. The modeling of turbulent flow addresses theoretical computational simulation methods and experimental methods such as wind tunnel testing. Among the advantages of using Computational Fluid Dynamics (CFD), speed, cost reduction, and providing more information are highlighted, but the behavior of these programs is like black boxes and depends on the construction of the represented geometry.

In 2019, some authors claimed that it is unlikely that CFD will completely replace wind tunnels in the near future [10], but the evaluated results allow us to establish that the use of CFD simulations in conjunction with experimental designs in wind tunnels yields highly reliable results.

All areas of research benefit from the use of machine learning. For our case study, the use of machine learning for predicting wind behavior based on data obtained from wind tunnel experiments and data provided by CFD simulations is in preliminary stages. As algorithms advance and improve their learning with larger amounts of data, their efficiency in predicting wind behavior will increase.

Regarding the object of study, it is necessary to consider that most research is conducted on homogeneous canopies. In heterogeneous canopies, further study is needed to improve the understanding and precision of aerodynamic parameter evaluation, and progress is needed in studying tall canopies and canopies with significant variations in the height of their elements.

In fluid analysis, most research is oriented towards using the Eulerian approach to particle trajectory, generally analyzing wind flow. We consider it important to also analyze the phenomenon from the Lagrangian approach as it is useful for studying pollutant transport, suspended soil particles, pollen or seeds, as well as simulating the movement of wind-borne objects, allowing for detailed knowledge of particle trajectories and their final deposition.

In terms of the applicability of these methodologies, they are considered to have great potential for use in studying other fluid-crop interactions, for example: 1) in wildfire propagation, 2) in examining the physical behavior of vegetation with wind, 3) in evaluating bioaerosol behavior, 4) in microclimate studies, 5) in foliar fertilization of vegetables, 6) in analyzing seed and pollen dispersion flows, 7) in plant flowering, and 8) in studying wind erosion in crops.

Despite significant advances made in the last five years, it is important to continue doing research addressing the topic, expanding the study from other perspectives such as those proposed in this work. Further investigation into the degree of porosity and varietal influence of elements that make up windbreak curtains is still necessary, as windbreaks remain a relevant method for wind dissipation and control in crop fields.

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