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Numerical Analysis Used to Predict the Spread of COVID-19 in a Classroom: TecNM Campus Sur de Guanajuato Case Study

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ABSTRACT

This paper examines the impact of indoor airflow, both natural and forced, on the dispersion and distribution of respiratory droplets produced by the act of sneezing in the context of viral respiratory infections, including but not limited to SARS-CoV-2 (Covid-19), Mpox (monkeypox), and other viral diseases. A numerical analysis was performed to examine the potential safety zones and the impact of ceiling fan usage in a classroom at the Tecnológico Nacional de México (TecNM) Campus Sur de Guanajuato, which features two windows and one door. The present study employs a simulation of the sneezes of twenty students and one teacher, with a distance separation of 1.5 m, within a classroom environment characterized by natural ventilation. The study is performed utilizing Computational Fluid Dynamics (CFD) in conjunction with the Discrete Phase Modelling (DPM) approach to capture the trajectory of particulates. Furthermore, the Navier-Stokes equations are employed to resolve the airflow field within the classroom numerically. The results demonstrate the considerable impact of airflow generated by ceiling fans on the dispersion of particles. The safety zones are situated close to the classroom walls, and the teacher is safeguarded if the ceiling fans are operational and the teacher is upright.

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1. INTRODUCTION

In the contemporary landscape, respiratory infectious diseases, notably exemplified by the Coronavirus 2019 (COVID-19) pandemic or monkeypox (Mpox), manifest a significant contributors to mortality rates, economic downturns, and disruptions within societal structures (Li et al. 2020). A deep comprehension of the intricate mechanisms underlying the dispersion and transmission of saliva-disease carrier droplets during respiratory activities, including sneezing and coughing, is imperative for effectively managing and curtailing the prevalence of such diseases. Additionally, enhancing our understanding of aerosolization and the dissemination of viruses constitutes a critical aspect in implementing preventive measures, encompassing practices such as social distancing, indoor ventilation enhancements, and consistent utilization of face masks. According to data from the Severe Acute Respiratory Infection (SARI) Information System of the Ministry of Health and the National Autonomous University of Mexico (UNAM) in Mexico, in January 2024, 16 hospitals are operating at full capacity with 100 percent occupancy of general hospital beds, likely due to the new COVID-19 subvariant JN.1 Pirola. Therefore, it is important to implement actions. Although it is challenging to measure spaces with disease transmission experimentally, it is possible to attempt to predict high-risk zones in enclosed spaces through numerical simulation, especially in places where a larger number of people gather, such as schools. The precise transmission mechanisms are still a subject of ongoing debate, but the respiratory droplet transmission mode is widely acknowledged as a key driver for sustained circulation of the influenza virus among individuals (Richard et al., 2020). Building upon this knowledge, Beans (2020) has substantiated the spread of COVID-19 through aerosolized droplets expelled by infected individuals during exhalation. The heightened infectivity rate of COVID-19 can be attributed to the augmented viral load present in the respiratory tract of hosts during routine respiration and social interactions (Yan et al., 2018; Bai et al., 2020).

NOMENCLATURE

α	thermal diffusivity	k_{eff}	effective thermal conductivity
α_ε	effective inverse Prandtl numbers for the turbulent dissipation,	K	kelvin temperature
α_k	effective inverse Prandtl numbers for the turbulent kinetic energy	m	meter
ρ	density	m_d	liquid droplet of mass
μ_{eff}	effective viscosity	mm	millimeter
μ_t	the turbulent (or eddy) viscosity	µm	micrometer
A_d	projected area of the droplet	P	pressure
C_d	drag coefficient	R_ε	the source term from renormalization
C_p	heat capacity	S_ε , S_k	user-defined source terms
C_μ	model constant	$\vec{S}$	force of the gravity
$\vec{F}_d$	drag force	S_T	heat of chemical reaction, and any other volumetric heat sources
$\vec{F}_g$	gravity force	t	time
$\vec{F}_{vm}$	virtual mass force	T	temperature
$\vec{F}_P$	pressure gradient force	$\vec{V}$	velocity vector
G_K	the generation of turbulent kinetic energy	$\vec{V}_d$	drag velocity
k	thermal conductivity	$\vec{V}_s$	droplet slip velocity

The existing guidelines about social distancing and face mask usage reveal a notable absence of comprehensive knowledge in this domain. Moreover, these guidelines often rely on outdated research findings as highlighted by Asadi et al. (2020) and Bourouiba (2020). In contrast, recent studies by Mittal et al. (2020) and Jayaweera et al. (2020) have provided empirical evidence supporting the assertion that the initial stages of airborne viral disease transmission primarily involve the dissemination of virus-laden droplets propelled through coughing and sneezing. These expelled droplets serve as vehicles for the dispersion of airborne particles near infected individuals, thereby contributing to the spread of the disease.

Several studies have focused on modeling the transport of aerosols to the transmission of COVID-19. One notable example is the research conducted by Feng et al. (2020), who developed a computational fluid-particle dynamics (CFPD) model. This model was employed to simulate the transport, condensation/evaporation, and deposition of droplets carrying SARS-CoV-2 (COVID-19) emitted through coughs. The simulations were conducted within a confined space, specifically a 27 m^3 volume cube, considering different wind velocities and humidity levels.

Perić and Perić (2020) analyzed the use of face masks during the global COVID-19 pandemic and studied the hypothesis that the impaired protection is related to imperfect fitting of the masks, provoking the leakage of airflow containing virus-transporting droplets. Fluid dynamics and numerical calculations have shown that mask gap heights greater than 0.1mm have failed to fulfill FFP2 or FFP3 standards.

Zhao et al. (2005), employed numerical analysis to examine the distribution of droplets during the sneezing process and confirmed that sneezing resulted in droplets traveling longer distances compared to breathing, thereby posing an increased risk of SARS infection to individuals nearby. On the other hand, Zhu et al. (2006), demonstrated that the transport characteristics of saliva droplets resulting from coughing can vary based on their size, they highlighted that these droplets are capable of traveling distances greater than 2 meters in a calm indoor atmosphere. This observation emphasizes the potential for airborne transmission of infectious particles and underscores the need for appropriate preventive measures. However, the study can be improved by analyzing a chaotic indoor atmosphere, which is the most realistic scenario, due to the use of ceiling fans or air-conditioning.

Bhardwaj and Agrawal (2020) investigated the drying time of respiratory droplets expelled by individuals infected with COVID-19. The study involved an evaluation of various factors, including droplet contact angle, volume, temperature, and environmental humidity. The researchers emphasized the significance of drying time as a critical factor in infecting another individual. In a series of studies, Wan and Chao (2006) and Wan et al. (2007) explored the impact of ventilation systems on infection risks associated with expiratory droplets. Their research revealed that unidirectional-upward ventilation systems are particularly effective in mitigating the effects of small droplet distributions, while single-side-floor ventilation systems are more beneficial in managing larger droplet distributions.

Examining the fluid dynamics of respiratory droplets in the context of face mask usage, Dbouk and Drikakis

(2020) conducted a comprehensive analysis. They investigated the interaction modes, such as rebound, stick, and penetration, of saliva droplets onto the fibrous porous surface of face mask filters induced by a mild coughing incident. The findings demonstrated that wearing a face mask reduced the travel distance of droplets by approximately half compared to not wearing a mask. Moreover, the study revealed that the distance traveled by droplets increased with successive cough cycles. Another study conducted by Mahdi et al. (2021), computational fluid dynamics (CFD) was employed to examine the impact of airflow within an indoor environment, specifically a classroom, on the distribution and transmission of droplets emitted during speaking and coughing events by an infected individual. The findings of this investigation shed light on the considerable influence of factors such as air-conditioning systems and the presence of open windows in the proximity of the infected person, in effectively reducing the dispersion of environmental pathogens. However, it is worth noting that the study conducted by Mahdi et al. (2021) did not encompass the examination of mechanical fans, which are a prevalent form of ventilation commonly found in developing countries. Consequently, the influence of mechanical fans on the distribution and transmission of droplets emitted by an infected individual within an indoor setting remains unexplored in their research. In a study conducted by Duan et al. (2021), discrete phase modeling was utilized to simulate the diffusion characteristics and concentration distribution of droplets under different temperatures and exhalation positions within a bus environment. The objective of the investigation was to identify seats with lower risk levels based on the simulations conducted, thereby providing valuable recommendations for the reduction of transmission risks. In a related study, Gorbunov (2021) developed and applied a fast-computational 3D model that incorporates fluid dynamics, heat transfer, mass transfer, and diffusion of diluted species. The model was utilized to assess the dispersion of aerosol particles in various environments. The findings revealed that aerosol particles within the size range of 10 µm to 100 µm, which have the potential to carry SARS-CoV-2 (COVID-19) viruses, can travel distances exceeding 30 meters under specific atmospheric conditions. These results underscore the importance of understanding aerosol dispersion patterns and their potential impact on viral transmission in different settings. However, none of the works mentioned above include droplet distribution analysis using mechanical ventilation as ceiling fans which is the kind of ventilation used in the TecNM campus Sur de Guanajuato.

This paper studies the distribution of droplets laden with a virus such as COVID-19 or Mpox and its variants caused by sneezing of different persons inside a classroom of 7.4 m x 8.1 m x 2.5 m (length, width, height), considering twenty seating students with an average height of 1.73 m, in the presence of flow patterns created by the ventilation system, which are ceiling fans and natural ventilation.

Different scenarios were created to determine the danger and safety zones inside the classroom. In this study, the diffusion and motion of particles in the environment are treated as a three-dimensional, transient, and turbulent model. Lagrange's approach is adopted, utilizing the discrete phase model specifically for the liquid phase, which involves injected water (due to the small size of viruses (150 nm)) droplet particles, simulating droplets laden with any kind of virus. To calculate the fluid velocity field considering specific boundary conditions, the Reynolds-averaged Navier-Stokes equations (RANS) were employed. The standard k-ε turbulence model is also utilized to characterize the fluid flow. The findings of this investigation identify the safe and risky locations for each student and teacher under different scenarios, this research offers valuable insights for implementing measures to mitigate the transmission of infectious droplets.

2. Methods

The methodology applied follows the numerical methodology for Eulerian-Lagrangian approach. The mathematical model and a description of the numerical model setup are presented in this section.

2.1 Mathematical Model

Numerical modeling of flow dynamics of the transmission of COVID-19 was performed in two steps. First, a steady-state classroom's turbulent airflow condition was simulated using the RNG k-ε model. In the second step, water droplets, which could contain COVID-19, Mpox, or another risky disease, were injected in three periods of time and all the details about the DPM used are presented in Table 1, simulating the sneezing elapsed time of the infected person standing in the classroom and tracked using the Eulerian-Lagrangian method.

The saliva expelled during a sneeze was divided into three injection times due to the observation that the amount of saliva expelled in a sneeze varies significantly from one instance to the next. According to the literature, three different mass flow rates and three tracks were used to describe the amount of saliva in each period. The azimuthal angle graphically represents the formation of a cone at the moment of expelling saliva droplets, which deforms due to the action of gravity and particle velocity until the end of the third period at 0.5 seconds. The model used for evaporating species is called Diffusion-controlled, because in our case, the rate of vaporization is slow. It can be assumed to be governed by gradient diffusion, with the flux of droplet vapor into the gas phase being related to the difference in vapor concentration at the droplet surface and in the bulk gas.

2.2 Airflow modeling

According to Mirzaie et al., (2021), the general equations of mass conservation Eq. (1), momentum Eq. (2), and energy Eq. (3) for the incompressible steady airflow are given as:

$$\frac{\partial \rho}{\partial t}+\nabla \cdot\left(\rho \vec{V}\right)=0 \qquad (1)$$

Table 1 Details of DPM for water liquid particle

Parameter	Period of time 1	Period of time 2	Period of time 3
Interaction	Interaction with continuous phase		
Physical models	Two-way turbulence coupling, Stochastic collision, and Breakup		
Injection type	cone		
Material	Water-liquid		
Diameter distribution	Rosin-Rammler-logarithmic		
Evaporating species	Water-liquid		
Vaporization/Boiling model	Diffusion-controlled		
Temperature	310 K		
Velocity magnitude	44.44 m/s		
Cone angle	45°		
Outer radius	0.01m		
Min. diameter	2 μm		
Max. diameter	100 μm		
Mean diameter	51 μm		
Turbulent dispersion	Discrete random walk model and random eddy lifetime		
Injection time (s)	0 to 0.1	0.1 to 0.2	0.2 to 0.5
Azimuthal angle	0 to 360◦	0 to 360◦	0 to -180◦
Mass flow rate (kg/s)	1.8×10^{-2}	9.0×10^{-3}	4.5×10^{-3}
Tracks	84,575	169,150	253,725

Table 2 Computational settings of the sneeze in the classroom simulation

Boundary	Parameter		
Fluid Domain	Solver	Pressure based	Transient
	Gravity	9.81 (m/s^2)	Axis y
	Viscous	k-ε	realizable
	Scheme: Coupled	Second order	
Ceiling fans	Frame motion	Speed: 300 rpm constant	Rotation-axis direction: y
Students Floor Teacher Ceiling	Type: wall	DPM Boundary Conditions (BC) Type: trap	
Door	Type: pressure-inlet	Initial temperature: 300 K	DPM BC Type: Escape
Window 1 Window 2	Type: pressure-outlet	Backflow Temperature: 300 K	DPM BC Type: Escape

$$\rho\left(\frac{\partial \vec{V}}{\partial t}+\vec{V}\cdot\nabla\vec{V}\right)=-\nabla P+\mu_{eff}\nabla^2\vec{V}+\vec{S} \tag{2}$$

$$\rho\frac{\partial T}{\partial t}+\rho\vec{\nabla}\cdot\left(T\vec{V}\right)=\nabla\cdot\left(\frac{k_{eff}}{C_p}\nabla T\right)+S_T \tag{3}$$

where, ρ , $\vec{V}$ and P , are the air density (kg/m^3), velocity vector (m/s), and pressure (Pa), respectively, μ_{eff} is the effective viscosity (Pa · s), T is the temperature (K), k_{eff} is the effective thermal conductivity, C_p is the heat capacity (J·K^{-1}), $\vec{S}$ is used to denote other forces, such as gravity, which are acting on the fluid and S_T includes the heat of chemical reaction, and any other volumetric heat sources.

The Multiple Reference Frame (MRF) modeling was used to simulate the rotation of the fans and their interaction with the air inside the room in a steady state and for transient sliding mesh model (SMM) was used, as well as with the particles resulting from a sneeze. Consequently, five control volumes were defined: four rotating fluid zones corresponding to each ceiling fan, and one stationary fluid zone representing the air in the room, along with the corresponding interface. The boundary conditions are shown in Table 2.

2.3 Turbulence Modeling

The RNG k-ε turbulence model has been used extensively for simulating the airflow in indoor environments and was shown to be a suitable model by Tsan-Hsing et al. (1995). The corresponding transport equations for the turbulent kinetic energy *k* and dissipation rate *ε* are given as:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)= \frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right)+G_K-\rho\varepsilon+S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)= \frac{\partial}{\partial x_j}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_K)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \tag{5}$$

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{6}$$

$$k_{eff}=\alpha C_p\mu_{eff} \tag{7}$$

Where G_K is the generation of turbulent kinetic energy due to the mean velocity gradients. S_ε and S_k are user-defined source terms in our case we did not define source terms, and R_ε is the source term from renormalization (Mirzaie et al., 2021; Wenzhu et al., 2021). In Eqs. (4) and (5) α_k and α_ε are effective inverse Prandtl numbers for the turbulent kinetic energy and its dissipation, and $C_{1\varepsilon}=1.42$ and $C_{2\varepsilon}=1.68$ are model constants, according to Mirzaie et al. (2021). In Eq. (6) $C_\mu=0.0845$ is derived using RNG theory, and Eq. (7) is the effective thermal conductivity for the RNG k-ε model according to the Academic Research Fluent, Transport Equations for the RNG k-ε Model, theory Guide, ANSYS, Inc. In Eq. (7) α is the thermal diffusivity calculated with the effective inverse Prandtl numbers.

2.4 Discrete Phase Modeling

After airflow modeling, the particle trajectory analysis is used. The droplet's Lagrangian phase equations were discretized employing implicit numerical schemes at second order with two-way coupling and a quasi-steady evaporation model. Second-order temporal and spatial discretization of the governing equations was used in all scenarios (Ritos et al., 2024). In the Lagrangian framework, the equation of conservation of momentum for a liquid droplet of mass m_d (Ritos et al., 2024) is given by

$$m_d\frac{d\vec{V}_d}{dt}=\vec{F}_d+\vec{F}_P+\vec{F}_{v\,m}+\vec{F}_g \tag{8}$$

Where, the drag ($\vec{F}_d$), pressure gradient ($\vec{F}_P$), gravity ($\vec{F}_g$), and virtual mass ($\vec{F}_{v\,m}$) forces are calculated in implicit way for the Fluent ANSYS code. The drag force calculates the force on a material particle due to its velocity relative to the continuous phase based on:

$$\vec{F}_d=\frac{1}{2}C_d\rho A_d\left|\vec{V}_s\right|\vec{V}_s \tag{9}$$

Where C_d is the drag coefficient, $\vec{V}_s=\vec{V}-\vec{V}_d$ is the droplet slip velocity, and A_d is the projected area of the droplet (Mahdi et al., 2021; Ritos et al., 2024).

2.5 Numerical Modeling

The governing equations were solved by the ANSYS-Fluent-21 (© 2024 Copyright ANSYS, Inc) code that uses the finite volume approach. A polyhedral un-structured mesh was created with quadratic elements. The SIMPLE algorithm is used as coupling between pressure and velocity field. The minimum remaining convergence scale is settled in the order of 10^{-4} to solve the flow field, and 10^{-5} for momentum equations and turbulence model. In this study, first resolved the fluid field in steady-state, and then injected the particles simulating a sneeze in a transient way. Droplets expelled from the mouth with an area of $7.0\text{X}10^{-4}$ m^2 are considered. A uniform distribution of droplet sizes from small (2 µm), medium (51 µm) to large (100 µm) are considered using Rosing-Rammler-Logarithmic for diameter distribution. These values were selected according to the experimental results (Han et al., 2013) and recommendations of Kotb and Khalil (2020). The total number of droplets used was 253,725 for 3 students more than 95,000 reported by Pendar and Páscoa (2020). The temperature of droplets is set to 310 K, according to the conditions of the area, an ambient temperature of 298.15 K and 0% humidity were considered. The expelled velocity of particles is 44.44 m/s. Particle injection conditions, including diameter, mass flow rate, velocity, injection time, and other parameters used in the analysis are listed in Table 1.

Assumptions used in this simulation were taken from Mirzaie et al. (2021) and are: Temperature variations are negligible; sneeze emits only particles/droplets; droplet/particle sizes listed in Table 1; the humidity was not considered in the model; no-slip conditions between phases is assumed; virus-infected droplets are treated as particles; student bodies and their thermal plume (due heat generation) are neglected.

A pressure inlet condition with 300 K temperature was established for the door and a pressure outlet condition for windows with the same temperature. For the interactions between droplets and different surfaces, the trap condition is imposed on the surfaces of students, floor, and ceiling, and the escape condition is used for the inlet (door) and outlet (windows), and natural ventilation, pressure outlet was atmospheric. Furthermore, a 5% turbulence intensity at the inlet is considered. A grid independence study was performed, and the results indicated that increasing the number of grid elements from 2,163,831 to 3,561,554 did not significantly change the flow field. To capture the 0.5 s that the sneeze lasts, a time step of 0.001 s was used. After 0.5 seconds of physical time, a time step of 0.005 s was used, and the complete simulations lasted 3.5 s.

2.6 Numerical Setup

Figure 1 shows a schematic of a classroom with a teacher, twenty seating students, and four ceiling fans on the roof. In addition, the dimensions of the classroom and the position of all persons are included for a more detailed examination of the results.

The non-slip and trap boundary condition for floor and ceiling is used. Moreover, boundary conditions in the inlet at the door include pressure inlet. At the outlets in the windows, the pressure outlet and escape boundary conditions are set. The CFD model was used to simulate the transfer and dissemination of spherical particles while

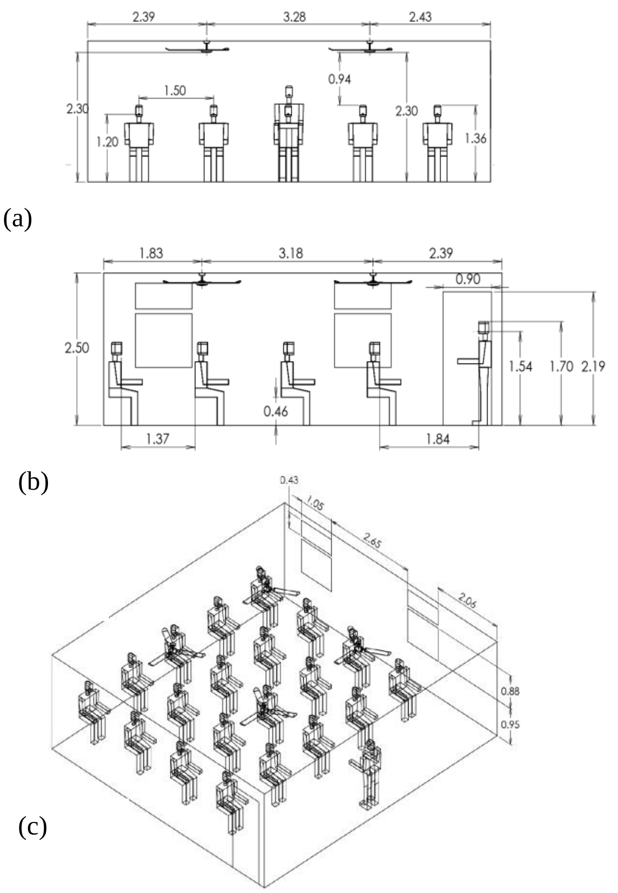

Fig. 1 Classroom geometry and schematics. (a) Front view, (b) side view, and (c) isometric view. All numerical values are in meters

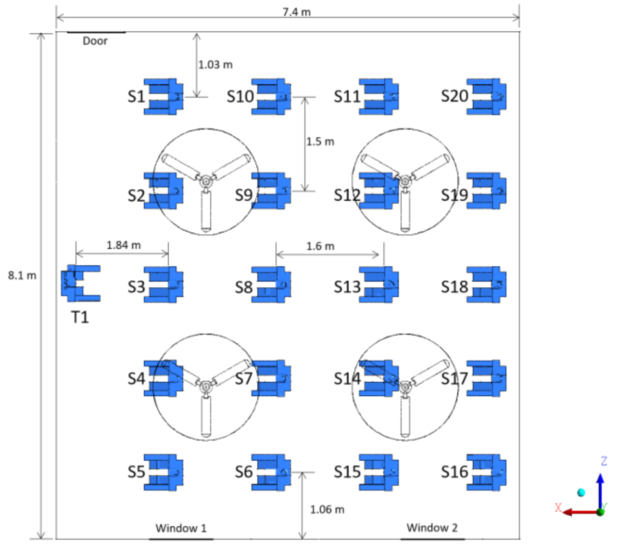

Fig. 2 Schematic of top view of the classroom

sneezing in the classroom.

The mouth of the person was modeled by injecting the particles in a circle with a diameter of 0.03 m. Since small particles have less inertia, and they evaporate immediately after leaving the mouth and remain suspended in the air, the aerosol particles are the most common causes of contamination of healthy people indoors (Gralton et al., 2011), hence, the study mainly focused on smaller particles.

The particle discharge velocity in sneezing was equal to 44.44 m/s and the total number of particles was estimated at 253,725. According to studies on sneezing by Mittal et al. (2020), Jayaweera et al. (2020), Zhao et al. (2005), Duan et al. (2021), and Pendar and Páscoa (2020), the particle diameters selected have extended the droplet sizes dispersed in typical sneezing to include: minimum diameter of 2 µm, maximum diameter of 100 µm and mean diameter of 51 µm. For ceiling fans an angular velocity of 300 rpm is used, which is the maximum operation speed according to the model and brand.

2.7 Scenarios Studied

In this research, six scenarios were considered. The first scenario corresponds to the situation where the teacher sneezes, with ceiling fans turned on and off. In the second scenario, 3 students (S1, S2, and S3) sneeze to evaluate the safety zones. A third scenario (S6, S8, and S10) from the second line in front of the teacher, sneezes. Students from the third line (S11, S13, and S15) sneeze in a fourth scenario. In a fifth scenario students from back to the classroom or fourth line sneeze (S16, S18, and S20). Finally, in the last scenario, the students under ventilators (S2, S4, S7, S9, S12, S14, S17, and S19) were selected to sneeze at the same time, to evaluate the dispersion of droplets expelled by sneezing. The dimensions and the specifications of the classroom and the seats from the top view are presented in Fig. 2.

3. Results

The present numerical model for DPM was validated by comparison with Chen and Zhao (2009) of a 10 µm droplet expelled by sneezing at 35 m/s. It is assumed that the droplets leave the mouth at a temperature of 310.15 K, and the room temperature is 298 K. The distances vertical and horizontal show a good agreement between the present predictions and the results of Chen and Zhao (2009), about 5%.

Figure 3 to Fig. 7 show a comparison among ceiling fans on (column right side) and off (column left side) images, 3.5 seconds after sneezing, which is shown in row a) streamlines in an isometric view of the classroom. In row b) a lateral view, vectors on plane XY which split symmetrically the students in the row correspondent. In row c) shows the superior view shows vectors on a plane aligned to XZ at the height of 1.20 m which corresponds to the location of the student's mouth from the floor.

Table 3 shows the average velocity and mass flow rate results according to the boundary conditions presented in Tables 1 and 2, corresponding to pressure inlet at the door and pressure outlet at both windows, incorporating the interaction of the ceiling fan flow when they are operating. The operation of the fans causes a decrease in the inlet velocity through the door and the outlet velocity through the windows, resulting in a reduction of the average mass flow rate exiting through the windows and entering through the door.

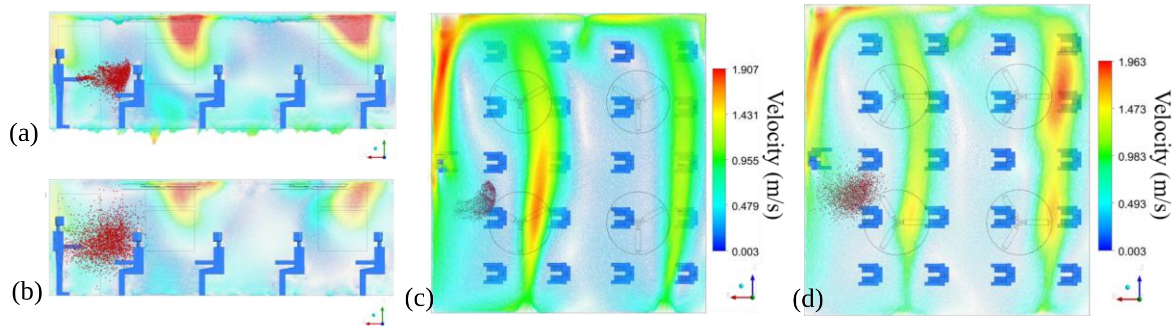

Fig. 3 Teacher sneezes at 3.5 s with ceiling fans on (b), (d); ceiling fans off views (a) and (c). (a) and (b) show a lateral view with vectors on plane XY which split symmetrically the classroom. (c) and (d) depict a top view of the classroom, showing vectors on a plane aligned to XZ at the height of 1.20 m corresponding to the location of the student's mouth from the floor

Table 3 Results for the field flow

	Door	Window 1	Window 2
Ceiling fans on			
Average of velocity (m/s)	3.21	2.24	2.30
Average of mass flow (kg/s)	$18.98x10^{-3}$	$11.63x10^{-3}$	$13.40x10^{-3}$
Ceiling fans off			
Average of velocity (m/s)	3.39	2.48	2.55
Average of mass flow (kg/s)	$20.51x10^{-3}$	$13.29x10^{-3}$	$13.63x10^{-3}$

Table 4 Results for the field flow at ceiling fans

	Ceiling fan 1	Ceiling fan 2	Ceiling fan 3	Ceiling fan 4
Ceiling fans on				
Average of velocity (m/s)	6.19	6.12	6.20	6.22
Average of mass flow (kg/s)	$8.72x10^{-6}$	$8.47x10^{-6}$	$5.52x10^{-6}$	$4.75x10^{-6}$
Ceiling fans off				
Average of velocity (m/s)	0.63	0.77	1.57	1.58
Average of mass flow (kg/s)	$5.32x10^{-7}$	$4.02x10^{-7}$	$1.48x10^{-6}$	$7.21x10^{-7}$

Table 4 shows the velocity and mass flow rate within the volume of the four ceiling fans, both when they are operating and turned off. The ceiling fan 1 is over S12 student, ceiling fan 2 is over S14 student, ceiling fan 3 is over S4, and ceiling fan 4 is over S2. Table 4 shows that the average velocity of the four ceiling fans is 6.18 m/s when they are on and less than 1.6 m/s when they are off. A variation in the mass flow rates is also observed. The highest mass flow rates in the operating fans correspond to those located closer to the wall opposite to the professor's position.

3.1 Scenario 1

For the first scenario, the trajectory of droplets caused by teacher sneeze is analyzed. In Fig. 3 is observed that, in the case of the ceiling fans on (Fig. 3 (b) and (d)), a dispersion of saliva drops is generated, which means that it can reach the students (S3 and S4) in front of the teacher.

Meanwhile, in the case of ceiling fans off (Fig. 3 (a) and (c)), the cloud of saliva droplets moves together, which means there is no particle dispersion. According to Fig. 3, it can be seen that in both cases the droplets touched the faces of students S3 and S4. The cloud is flatter and less dispersed when the ceiling fans are off. Particles with ceiling fans on, travel more distance than with ceiling fans off. With ceiling fans on, particles travel more than 1.84 m from the teacher's mouth and surpass the height of the teacher, 1.70 m.

3.2 Scenario 2

The analysis was carried out with the students in the first row (S1, S3, and S5) sneezing simultaneously, the nearest to the teacher. According to Fig. 4, it can be seen that the direction and trajectory would not affect risky areas of the teacher, such as the face.

According to the side and front view of Fig. 4, the trajectory even reaches the wall where the blackboard would be, without affecting the teacher for potential infection. With ceiling fans on (Fig. 4 (b) and (d)), the particles from S1 get out of the classroom. Fig. 4 shows that the particles ejected by the student in front of the teacher could touch him.

3.3 Scenario 3

In the third scenario, an analysis was performed with the sneezes simultaneously of three students from the 2nd row (S6, S8, and S10). According to Fig. 5, it is observed that the trajectory is practically similar for the student near

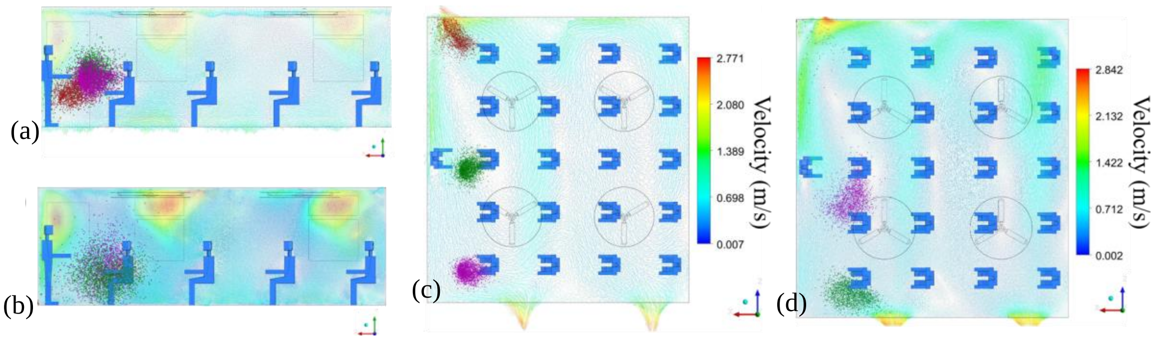

Fig. 4 Students S1, S3 and S5 sneeze at 3.5 s with ceiling fans on (b), (d); ceiling fans off views (a) and (c). (a) and (b) show a lateral view with vectors on plane XY which split symmetrically the classroom. (c) and (d) depict a top view of the classroom, showing vectors on a plane aligned to XZ at the height of 1.20 m corresponding to the location of the student's mouth from the floor

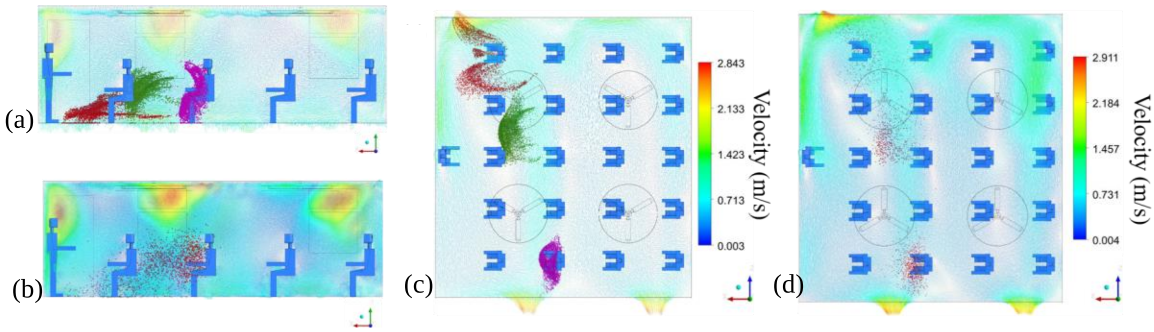

Fig. 5 Students S6, S8, and S10 sneeze at 3.5 s with ceiling fans on (b), (d); ceiling fans off views (a) and (c). (a) and (b) show a lateral view with vectors on plane XY which split symmetrically the classroom. (c) and (d) depict a top view of the classroom, showing vectors on a plane aligned to XZ at the height of 1.20 m corresponding to the location of the student's mouth from the floor

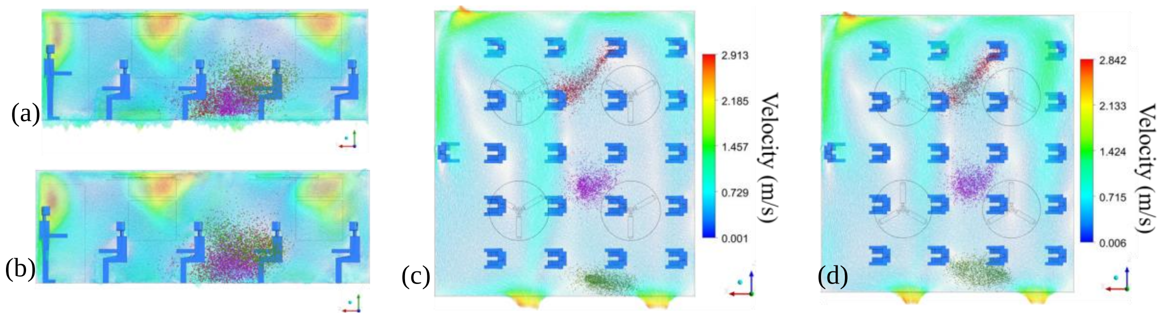

Fig. 6 Students S11, S13, and S15 sneeze at 3.5 s with ceiling fans on (b), (d); ceiling fans off views (a) and (c). (a) and (b) show a lateral view with vectors on plane XY which split symmetrically the classroom. (c) and (d) depict a top view of the classroom, showing vectors on a plane aligned to XZ at the height of 1.20 m corresponding to the location of the student's mouth from the floor

the window (S6) with ceiling fans on and off. However, for the other two students (S8 and S10) it seems that the ceiling fan attenuated the trajectory reached by the expelled saliva. In Fig. 5, it can be noticed that the ejected saliva cloud does not travel around the classroom. From Fig. 5 (a) and (c), it is observed that the trajectory where the ceiling fans are turned off goes directly to the floor, instead with the ceiling fans on (Fig. 5 (b) and (d)), it disperses reaching the area of the head of the students in the first row (S1, S2, and S3).

Figure 5 shows how the streamlines influence the dispersion of the droplets expelled by the students who sneezed, we can see how the streamlines by airflow change the trajectory of particles. In both cases, particles travel over 3 m in the direction of the teacher, and the S10 expelled the largest distance, followed by S8 and the S6, which are the less dispersed sneeze.

3.4 Scenario 4

In this scenario with students S11, S13, and S15 sneezing simultaneously both trajectories are very similar, however, there are small differences. The S15 student, situated near the window in Fig. 6, whose green cloud colour is observed to be affected by the ceiling fans when they are in the 'off' position (Fig 6 (a) and (c)), is observed as the droplet cloud is closer to the window. As in the previous cases, it seems that the ceiling fans affected the

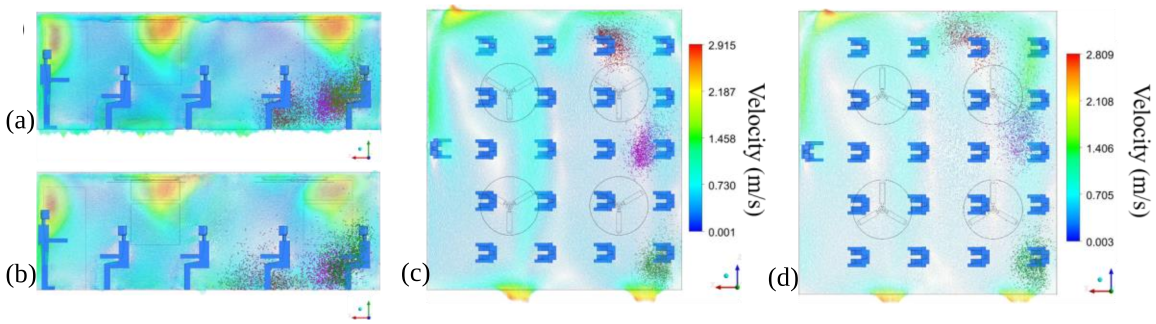

Fig. 7 Students S16, S18, and S20 sneeze at 3.5 s with ceiling fans on (b), (d); ceiling fans off views (a) and (c). (a) and (b) show a lateral view with vectors on plane XY which split symmetrically the classroom. (c) and (d) depict a top view of the classroom, showing vectors on a plane aligned to XZ at the height of 1.20 m corresponding to the location of the student's mouth from the floor

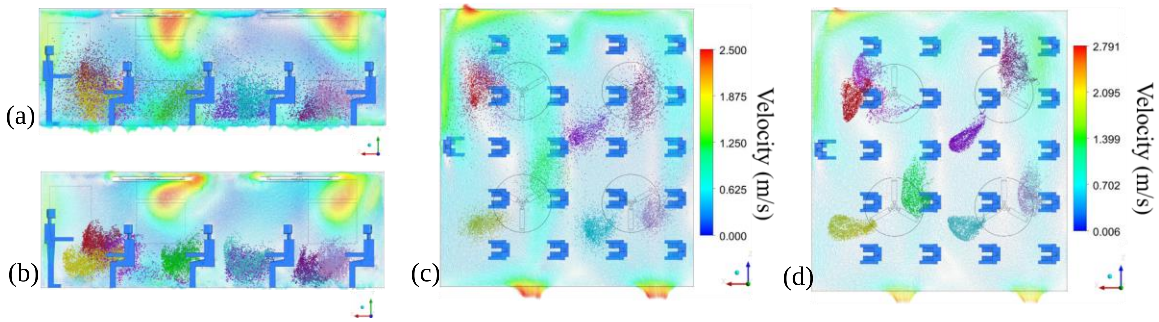

Fig. 8 Students S2, S9, S12, S19, S4, S7, S14 and S17 sneeze at 3.5 s with ceiling fans on (b), (d); ceiling fans off views (a) and (c). (a) and (b) show a lateral view with vectors on plane XY which split symmetrically the classroom. (c) and (d) depict a top view of the classroom, showing vectors on a plane aligned to XZ at the height of 1.20 m corresponding to the location of the student's mouth from the floor

trajectory of the student with the purple cloud, S13, where the cloud is more scattered in the classroom. In the absence of ceiling fans, S13 makes contact with only two other students, namely S7 and S14. Conversely, when the ceiling fans are in operation, S13 makes contact with a further student, namely S8.

According to Fig. 6, the cloud formed where the ceiling fans are turned on (Fig 6 (b) and (d)) is more concentrated in the hall and less dispersed beyond the row of rear students. In Fig. 6 it can be seen that in the row of students analyzed, the circulation of the airflow is less than in the other zones.

It can be seen that in the case with the ceiling fans on (Fig 6 (b) and (d)), they generate a dispersion of the cloud over students S13 and S15. The particles expelled by student S11 reach a shorter distance with the ceiling fans on than in the other case. In this scenario both cases are similar, however, the particles travel with ceiling fans on over 2 m away than with ceiling fans off.

3.5 Scenario 5

For students of the 4th row (S16, S18, and S20) sneezing simultaneously there are important differences. In Fig. 7 the red cloud, in the case of ceiling fans on (Fig 7 (b) and (d)), moves near the wall on the side of the door, more noticeable is the fact that ceiling fans off reduce the risk of the droplets touching any risky area in students.

The same effect of the ceiling fans off (Fig 6 (a) and (c)) causes the purple cloud to change direction and dispersion in student S18, generating a danger zone for a possible infection. For the case of the students near the window, the behavior is similar, however, for the case where the ceiling fans are off; the cloud is closer to the wall.

According to Fig. 7, the height of the clouds is similar in both cases, however, the case where it travels a longer distance corresponds to the red cloud and it is where the ceiling fans are on, although, it is below the face of the students sitting back of the classroom and travel more than 1.5 m.

The streamlines, as in the previous cases, show that the operation of the ceiling fans affects the distribution of the particles in each student, changing the direction of the particles for the three students S16, S18, and S20, as shown in Fig. 7. With ceiling fans on, particles from S20 reach over 2 m. In the lateral direction, particles from S18 travel more than 1.5 m.

3.6 Scenario 6

In this scenario with the students S2, S9, S12, S19, S4, S7, S14 and S17 S13, and S15 sneezing simultaneously, the ceiling fans fully affect each cloud´s trajectory. In the first row, near the teacher, the red and yellow colors have similar patterns with the ceiling fans on and off, as shown in Fig. 8. In the second row, the violet cloud dispersed and reached the subsequent students, implying a risk due to droplets reaching the face, for example.

The green and the purple clouds remained less dispersed with the ceiling fans on (Fig 8 (b) and (d)), unlike the case where the ceiling fans were off. In the fourth row, the direction of the clouds is similar. However, the purple cloud is more spread out with ceiling fans off (Fig 8 (a) and (c)). In the fifth row, the cherry-colored cloud presents a high displacement, generating a risk for the students near the wall.

For the pink cloud, the direction in both cases was opposite and for the case where the ceiling fans were off, it was more dispersed, according to Fig. 8. In Fig. 8(a) it can be seen that the height of the cloud for all the rows with ceiling fans on did not exceed the head of each student, this indicates that the direction of the ceiling fans flow pushed the sneezing clouds towards the floor. This is the desired effect for all sneezing students, but it was only present in the rows directly under the ceiling fans. With ceiling fans on, particles from S20 reach over 2 m. In lateral direction particles from S18 travel more than 1.5 m.

The S16, distance traveled along the X axis is minimum, approx. 0.6 m from the mouth of the student. The directions of the particles cloud are variable but the same direction in both cases is shown. For example, particles from S4 and S14 travel along the axis negative in Z, on the other hand, S7 and S17 move to the opposite side. When the ceiling fans are on, most of the particle cloud exceeds 1.36 m in height. Some even reach the professor's height of 1.70 m.

4. Discussion

So far, the six scenarios have been analyzed, about the velocity profiles, and their impact on particle drag. The CFD tool allows the determination of particles that touch a surface, is considered that students S1, S2, S20, and teacher T1, can belong to two conditions:

According to the determination of particles that touch a surface, the risk of each student is evaluated, to do it visually, Fig. 9 shows, that in case it is red, the students have a great risk of being infected because they were touched four times in the six proposed scenarios by drops from another person. The orange color shows the students who were touched by the saliva drops of other people in three different scenarios. In yellow, the students who are touched in two scenarios are shown. In green are the students who are touched in one scenario by drops from another person. Then in blue color, the students are not touched by anyone.

Figure 9 illustrates that positions S3 and S4 represent the greatest risk to students, as evidenced by four scenarios in which the saliva of another student or teacher came into contact with either a turned-off or turned-on ceiling fan. Students S16, S17, and S20 were not touched by the saliva of another student in any scenario.

After carrying out the count of particles deposited on the surfaces of the 20 students and the teacher. Practically the best conditions with ceiling fans off are for scenarios

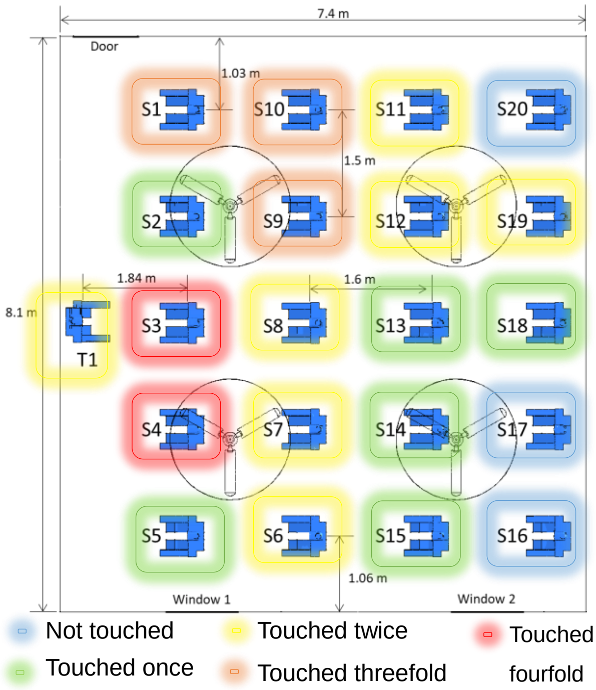

Fig. 9 Summary of the number of scenarios in which the student has had contact with the saliva of another student or teacher

1 and 3 because it is where fewer students are touched by saliva particles compared to ceiling fans on, for the other scenarios the ceiling fans on represent a better option.

5. Conclusion

Different scenarios were analyzed in a transient state on the trajectory of a sneeze in a classroom with 20 students and the teacher separated by 1.5 m, the distance recommended by the health authorities in Mexico without face mask wearing. The operation of ceiling fans has been observed to generate dispersion and, in some cases, alter the direction of sneeze particles.

The safest students or seats were S16, S17, and S20 because, in all scenarios with ceiling fans on or off, they were not touched by other students' saliva drops or the teacher.

The least secure were S6, S7, S8, S11, S12, and S19, because, in all scenarios, they were reached once by other students' saliva drops. Student S3 presents more risk than the other students because in all scenarios is reached by other students, and its saliva drops.

Those who were expelled and had contact with their saliva were S16, S17, and S20 in all scenarios. When the teacher sneezes, it is a potential risk for the S3 and S4.

The teacher in all scenarios is the safest person in the room, due to the standing up position that he/she maintains, the particles never reach his face while the students remain seated. This suggests that in any interaction between an individual in a standing position and another in a seated position, there is an increased risk of infection for the individual in a seated position, due to the direction of particle movement affected by gravity.

Even if the students and professors are vaccinated, the present study highlights the importance of using the face mask and recommends directing the sneeze towards the floor or covering it with the elbow or hands, because this would avoid generating a dispersion of small drops of saliva that can be potentially dangerous due to their possible viral load and if they touch any sensitive area of contagion.

According to the results obtained, it would be advisable to avoid seating students in S1, S3, S4, S9, and S10 indicating that alternatives could be employed as a solution in settings where resources are limited instead of ventilation strategies (e.g., HEPA filters, UV sterilization), that involve a cost. This is because they are touched in more than three scenarios, which would increase the risk of contagion. It is recommended to use axial flow ceiling fans, to avoid the dispersion of particles, or use the air conditioning that generates an axial flow from ceiling to floor. It would force the particles to be directed towards the floor and avoid a chaotic flow, this could be better than having the doors and windows open.

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Conflict of Interest

The authors have no conflicts to disclose

Authors Contribution

José Eli Eduardo González-Durán: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization; **Leonel Estrada-Rojo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization; **Julio Ortega-Alejos:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization; **Edgar G. Blanco-Diaz:** Writing – review & editing, Writing –original draft, Visualization, Resources, Formal analysis; **Juan Manuel Olivares-Ramírez:** Writing – review & editing, Writing –original draft; **Juan Manuel García-Guendulain:** Writing – review & editing, Writing –original draft.

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