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Case Report

Development of a cyclone separator for particulate matter control in fique bag production: A case study at Empaques del Cauca S.A.

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ABSTRACT

Environmental pollution has become a pressing global concern that poses significant health risks and socio-economic challenges. Developing countries are witnessing increased chronic diseases attributed to water and air pollution. This study focuses on Empaques del Cauca S.A., a Colombian company that manufactures fique bags for domestic and international markets. Due to the existing technological and technical infrastructure, the production process of these bags generates the emission of particulate material, specifically PM10 and PM2.5. Thus, developing a cyclone separator is proposed, following the V-quadrant methodology, incorporating the requirements of problem recognition and integrating it into design and simulation stages through computer-aided design and engineering. In this way, the results of the design and simulation of the Stairmand-type cyclone separator demonstrate the fulfillment of the functional, technical, and operational requirements established by the problem of the case study company. The cyclone separator achieved an 88 % average separation efficiency for particles between 1 and 10 μm. In addition, static studies on displacement and stress in the critical component of the outlet pipe indicate the optimum performance of stainless steel as a construction material, outperforming black steel plate. Stainless steel not only has minimal static displacement but also has maximum stress tolerance and operating speed limits. The materials proposed for the cyclone separators show commendable performance, especially for 10 μm particulate material (PM10). Both materials effectively eject zero particles per second into the air and collect the particles in the collector condenser with variable velocity profiles. In the case of the stainless-steel design, a marginal increase in particle collection is observed at specific velocity profiles, highlighting its overall efficiency. This research not only presents a satisfactory solution to reduce particulate emissions in the production of fique bags but also highlights the importance of material selection in the design of cyclone separators.

1. Introduction

Environmental pollution has grown at an accelerated rate, causing health problems for people, as well as having an impact on the social and economic spheres. In developing countries there is evidence of an increase in chronic diseases in people, mainly due to water and air pollution [1]. In the year 2019, roughly 9.0 million premature deaths were attributed to pollution. The predominant contributor to this alarming statistic was air pollution, encompassing both household and ambient air pollution, accounting for 6.7 million deaths during that year. Additionally, water pollution played a significant role, being linked to 1.4 million premature deaths [2].

In Colombia, the working population and industrial personnel lose an average of thirty-three years of healthy life due to environmental factors, which means an approximate cost of 10 billion pesos per year [3]; One of the main causes is linked to the development of the industrial sector, positioning itself as an important focus in air pollution by the emission of gases and particulate pollutants, due to the obsolete technological maturity machinery currently used in the different production processes [3].

The World Health Organization (WHO) estimates that approximately 7 million people die each year from the effects of inhaling particulate

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matter in polluted air. These particles have the ability to deeply penetrate the respiratory and cardiovascular systems, leading to conditions such as stroke, heart disease, lung cancer, chronic obstructive pulmonary disease, and respiratory infections, including pneumonia [4].

In this sense, the particulate material of greatest interest are particles with diameters smaller than 10 μm, due to their high penetration rate into the lungs during natural breathing of a living being. It is reported that particles between 2.5 μm and 10 μm are deposited in the trachea, bronchi and bronchioles, and particles smaller than 2.5 μm, including nanoparticles, are able to reach the interior of the pulmonary alveoli [5,6].

To prevent the deterioration of the environment in manufacturing industries and mitigate the harmful effects on people's health as a result of the expulsion of particulate matter, different technological solutions have been created, one of these are the particle separators which are responsible for isolating the polluting particles from the air flow expelled by the machines used in industrial processes.

In this sense, cyclonic separators use centrifugal force to separate solid particles from gases or liquids. The typical application involves recycling products or catalyst particles and purifying process streams before their release into the environment [7]. Electrostatic precipitators use electric fields to charge and separate particles from exhaust gases, commonly used in the steel and energy industries for emission control [8]. Baghouse filters with fabric media capture solid particulates from air streams, which is effective in cement production and mining [9]. Centrifuges segregate particles of different densities in liquid media and are applied in chemical and petrochemical industries [10]. Magnetic separators extract ferrous particles from non-metallic materials, which is crucial in recycling and mining [11]. Each technology offers distinct advantages, with selection based on process requirements, particle characteristics, and operational conditions, significantly impacting process efficiency, product quality, and environmental compliance.

However, cyclone separators offer a cost-effective solution for particle control in industrial applications, balancing efficiency and economic considerations [12]. Compared to electrostatic precipitators (ESPs), baghouse filters, centrifugal separators, and magnetic separators, cyclones present lower capital and operating costs due to their simple design and minimal maintenance requirements. While ESPs and baghouse filters may achieve higher efficiencies for fine particles, cyclones remove larger particles and can be enhanced with electrical forces to improve performance. Although each technology has advantages, cyclone separators offer a robust and economical option, particularly when considering implementation ease, operational costs, and maintenance aspects [13].

Regarding type separators, some research has shown that particle collision is essential in dynamic separators [14]. Caliskan [15] has demonstrated the ability of a novel cyclone separator to classify incoming particles into different size classes. Maammar [16] developed a mathematical model for particle trajectories in multimodal electrostatic separators. Tan [17] designed a separator to collect aluminum dust particles and showed the effect of different parameters on separation efficiency. Lim [18] presents a new design of cyclone separator with the ability to effectively aspirate aerosols from all directions over a range of 360° by adjusting the cut-off size without the need to change its geometry or flow rate, which can be effectively applied to PM2.5 or PM10 sampling. Caliskan [19] shows the influence of various parameters on the operating efficiency and classification potential of a cyclone classifier. The investigation shows that geometric relationships and operating conditions play a crucial role in influencing the selectivity and efficiency of the cyclone classifier. It was also found that using the cyclone as a classifier did not result in a significant change in separator performance. These results contribute to understanding the factors influencing cyclone classifiers and provide valuable insights for their optimization in various applications, including manufacturing companies based on agro-industrial products.

On the other hand, according to the Organization for Economic Cooperation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO), Latin America and the Caribbean supply 23 % of the world's agri-food exports, and this is expected to increase to 25 % by 2028 [20]. Colombia cultivates about 200 crops annually on 5,099,774 ha, with a total production of 63 million tons. Fique (Furcraea sp., family Agavaceae) is an Andean plant traditionally used to obtain fibers whose commercial applications are in the manufacture of ropes, twines, textiles, handicrafts, and packaging materials. These products represent 4 % of the total material obtained after processing and are available in the Colombian market throughout the year [21,22].

According to the above, the case study company Empaques del Cauca S.A., dedicated to the manufacture of fique bags products for the national and international market, emits in its production process particulate matter in a range of aerodynamic diameter equal or less than 10 μm and less or equal to 2.5 μm (PM10 and PM2.5) [23,24], because of its technological and technical production infrastructure. Therefore, the environmental conditions of workers and operators have been affected, presenting a high incidence of acute respiratory infections due to fique dust in the work area [25]. In addition, the particles are suspended in the production plant and impregnate the machinery, generating a dangerous visual obstruction to its operation. This waste also impacts on the environment outside the plant; the dust particles are expelled outside the company's premises without any filter, causing an environmental impact on the surrounding residential areas. For this reason, the company has established as a guideline the technological development of an automated solution for the control of fique dust residue as a continuous improvement and innovation of its production processes to contribute to the sustainable development of the region [26,27] and complying with Colombian Technical Standard NTC5517, which states in regarding environmental requirements for the manufacture of packaging, packing, twine, yarns, ropes and fabrics concerning air treatment, which requires particle extraction systems and personal protective equipment inside the plant [28].

In response to the identified problem, this article aims to develop a cyclone separator designed to reduce the particulate matter emission generated during fique bag manufacturing. The case study focuses on Empaques del Cauca S.A., which produces fique bags for the national and international markets. It highlights the importance of this technological advance in helping to meet the environmental requirements established by Colombian regulations for the manufacture of fique products.

2. Materials and methods

The development of the cyclone separator for the case study is based on the V-quadrant model methodology [29], taking into account the knowledge and system integration requirements for the different development and implementation processes (Fig. 1). For this particular case, the process consists of activities related to state-of-the-art research, technology watch, requirements specification, design, and validation.

Initially, an analysis of the particulate material's morphological characteristics, size distribution, and elemental composition was conducted through laboratory investigations. This analysis employed Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDX). The experimental procedures were carried out using a Tescan VEGA 3 SEM microscope equipped with an Oxford Instruments X-Max 50 EDS system. These characteristics were compared in terms of particle size: fine particles (PM2.5) versus coarse particles (PM10) aiming to identify design parameters of the prototype based in a most relevant characteristics obtained for the three families of cyclones that exist for the separation of particulate material (Table 1) [30].

Thus, based on the size of the particles generated in the company, the expected removal efficiency and the layout of the infrastructure of the production process in the manufacture of fique bags in the case study company (Fig. 2), the type of cyclone to be implemented was defined.

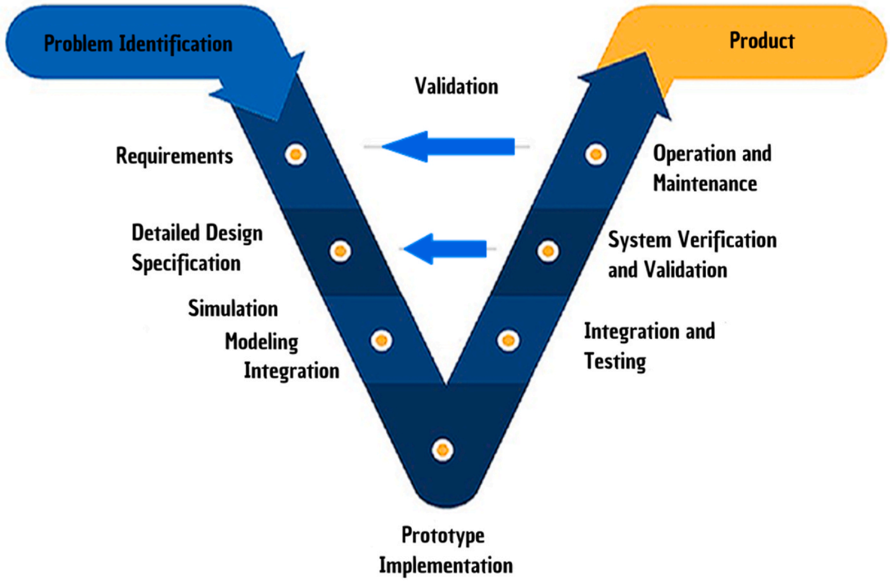

Fig 1. General design of the V-quadrant methodology implemented in this study.

Table 1
Removal efficiency range for different cyclone families cyclone family [30].

	Removal efficiency (%)		
Cyclone family	**PST**[a]	**PM10**	PM2.5
Conventional	70–90	30–90	**0–40**
High efficiency	80–99	60–95	**20–70**
High capacity	**80–99**	**10–40**	**0–10**

[a] PST Total Suspended Particles.

Next, the appropriate calculations of the critical parameters for the physical design of the cyclone were made, such as dimensions (height, width, diameter) and weight of the inlet, as well as outlet components of the particulate material. These calculations served as the basis for the computer-aided design (CAD). The CAD modeling was performed using SolidWorks software.

Once the virtual design was obtained, mechanical and dynamic studies of the cyclone were performed using computer-aided engineering (CAE) tools. For the finite element analysis (FEA), a tetrahedral mesh with an average element size of 2 mm and a refinement of 0.5 mm in critical areas was used. The boundary conditions included fixed support at the cyclone's base and the applied load from the particulate matter flow. The Von Mises stress criterion was used to evaluate the structural integrity.

For the computational fluid dynamics (CFD) analysis, a hexahedral mesh with approximately 500,000 elements was employed, with refinement near the walls and in the vortex finder region. The boundary conditions included a velocity inlet of 22 m/s, a wind pressure of 35.07 Pa at the inlet of the flow, and no-slip walls. The Navier-Stokes equations were solved using the k-ε turbulence model to simulate the flow behavior and particle trajectories within the cyclone.

Once the virtual design was obtained, mechanical and dynamic studies of the cyclone were performed using computer-aided engineering (CAE) tools, such as finite element analysis (Von Misses) and computational fluid dynamics (Navier Stokes).

3. Results and discussion

3.1. Design requirements and specifications

Fig. 3 shows the micrographs obtained by scanning electron microscopy, where some morphological characteristics of the residue obtained during the process of elaboration of the fique bags are evidenced.

Fig. 3a shows fibers with diameters greater than 80 μm, which are used in the manufacture of fique bags. It is worth noting that these fibers are typically about 1.5 m in length when extracted from the plant.

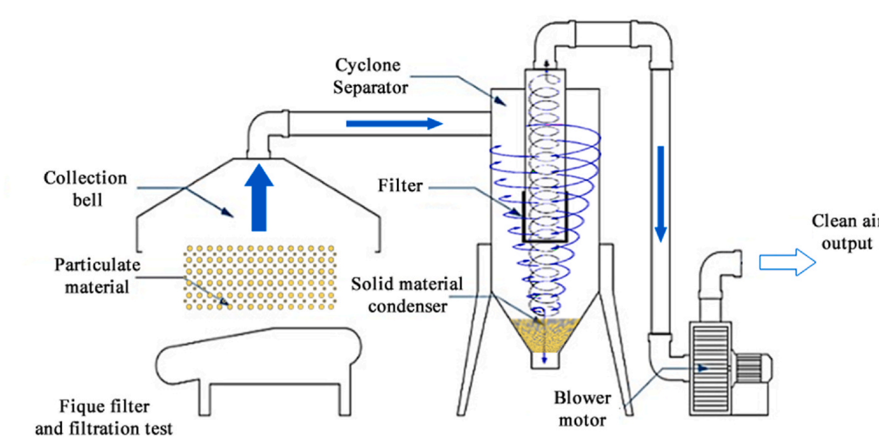

Fig 2. General particulate material control system.

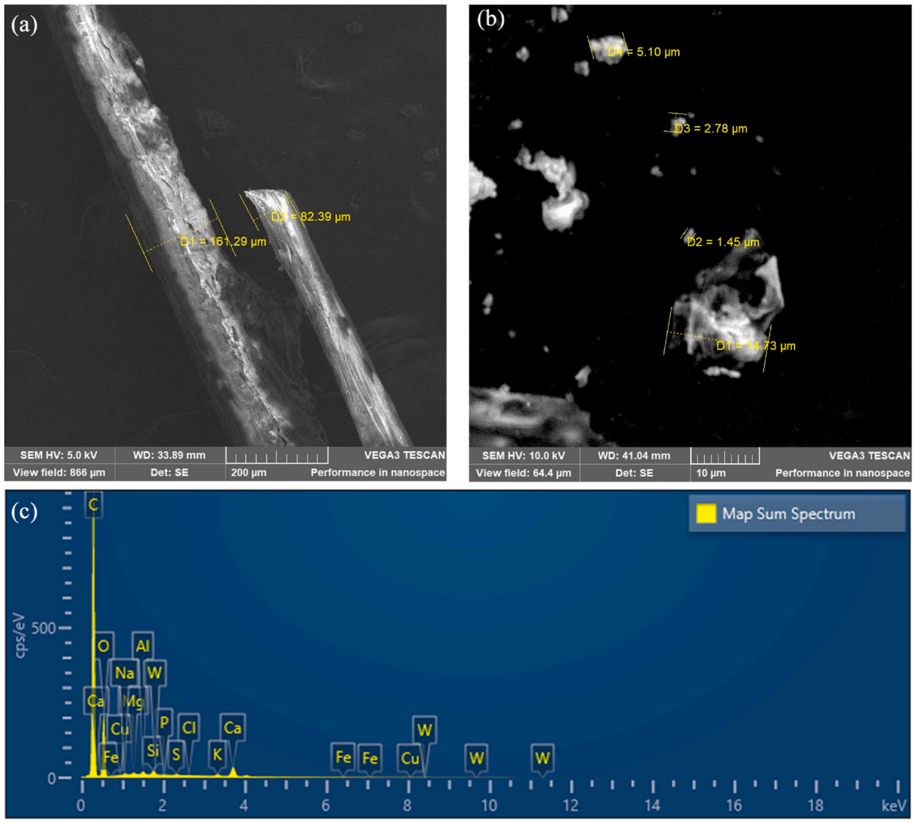

Fig 3. SEM micrographs showing (a) the long fibers used to make fique bags and (b) the resulting particulate material. (c) EDX profile of raw fique fibers.

Fig. 3b, shows a sample of the particulate material generated during the manufacturing process of the fique bags in the case study company, where an irregular geometry with average diameters between 15 and 1 µm is observed. Energy-dispersive X-ray spectroscopy (EDX) analysis of the material (Fig. 3c), indicates that it is composed primarily of organic matter, consisting predominantly of carbon, oxygen, as expected for natural polymers. The quantitative analysis revealed an estimated elemental composition (wt%, weight percent) as follows: C (71.8 wt%), O (26.3 wt%), Ca (0.92 wt%), Si (0.21 wt%), K (0.15 wt%), and Na (0.13 wt%). Additional elements were detected at concentrations below 0.01 wt%.

Considering the study of the size of the material generated in the production process of fique bags by means of scanning electron microscopy and a practical study of the critical environmental variables of temperature and relative humidity in the conditions of the production plant, the following design conditions are established: Average ambient temperature of 26.79 °C, average relative humidity of 58. 45 %, a high efficiency Cyclone, an inlet air flow rate of 724.3 m^3/h, particulate

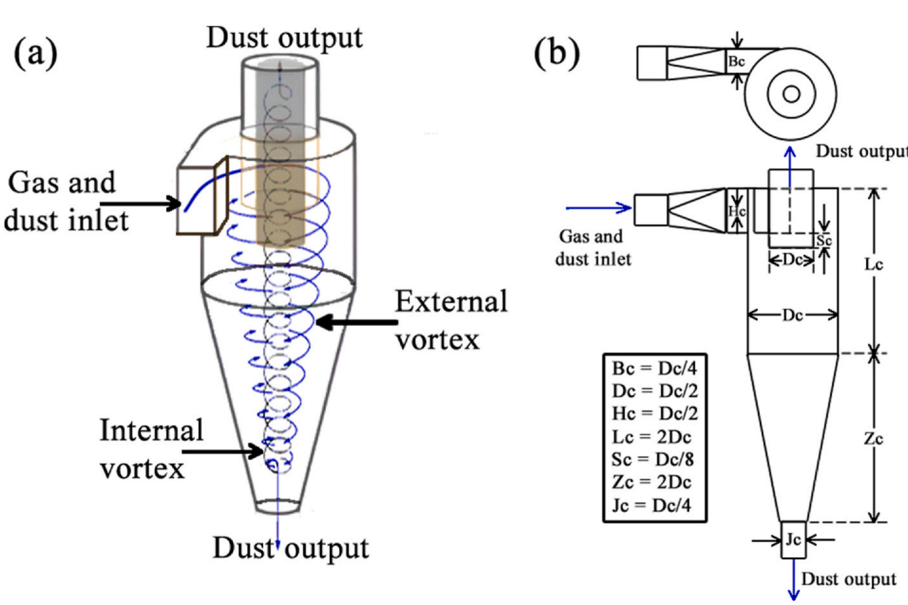

Fig 4. (a) Cyclone vortices and (b) cyclone dimensional relationships.

matter inlet velocity 22 m/s, particle density of 1740 gr/cm^3, average carrier gas (air) temperature of 26. 032 °C, carrier gas (air) density of 0.14 kg/m^3, carrier gas (air) viscosity 0.0000041 kg/ms and a particle size diameter set of 0.001 mm–0.003 mm - 0.004 mm–0.006 mm - 0.010 mm. Thus, based on this information the detailed design specification was then drawn up.

On the other hand, it is known that a cyclone, the gas path includes a double vortex, where the gas draws a spiral downward on the outside and upward on the inside (Fig. 4a). These cyclones are classified based on their dimensions, where the geometric parameters maintain a relationship with the diameter, Fig. 4b shows graphically the dimensional relationship of cyclones [31].

Thus, the ratio of cyclone dimensions as a function of defined diameter was determined by calculating each geometric design parameter. It should be noted that similar calculations have been made for Stairmand, Swift and Echeverry high efficiency cyclones. However, for reasons of space, the most relevant values for the Stairmand cyclone are presented (Table 2).

Based on these design parameters, the particle removal efficiency was mathematically determined for each type of cyclone in a range from 1 to 10μm, resulting in an efficiency that varies from 66 % to 99 %. These percentages are detailed in Table 3.

Here it can be observed that the removal of particles of 1μm size is not completely efficient for any of the cyclone types studied. However, this tendency increases with increasing particle size and reaches values up to 99 % for 10 μm particles.

Thus, given the efficiency obtained in the range of particles between 1 and 10 μm, it is considered that the high efficiency Stairmand cyclone could provide an effective separation of particles and a clean air discharge for the current conditions handled in the production of fique bags in the case study company.

In addition, Table 4 presents a comparison of the design parameters reported in the literature and the calculated values for cyclone diameter, pressure drop, velocity ratio, and inlet velocity, finding a reasonable correlation between the expected values for these characteristics and the selected Stairmand cyclone.

3.2. CAD modeling stage

In accordance with the proposed methodology and the specific design actions defined in the previous section, the computer aided design (CAD) of each component of the cyclone, including the base, the cone, the cover and the discharge pipe, is carried out (Fig. 5).

Table 2
Design parameters of the Stairmand type cyclone based on its diameter.

Data	Unit of measurement	Nomenclature	Nomenclature calculation	Value
Cyclone inlet area	m^2	A	Q/Vi	0,00915
Cyclone inlet height	m	A	a/Dc	0,15123
Cyclone inlet width	m	B	b/Dc	0,06049
Cyclone outlet height	m	S	s/Dc	0,15123
Cyclone outlet diameter	m	Ds	Ds/Dc	0,15123
Height of the cylindrical	m	H	h/Dc	0,45368
Total height of cyclone	m	H	H/Dc	1,20981
Height of the conical part of the cyclone	m	Z	z/Dc	0,75613
Diameter of powder outlet	m	B	S/Dc	0,11342
Cyclone diameter	m	Dc	Dc	0,30245

Table 3
Calculation of the most important aspects for the designed separator.

	Type cyclone		
Data	Stairmand	Switf	Echeverry
Percentage removal efficiency for 0.001mm particle size	66 %	67 %	67 %
Percentage removal efficiency for 0.0025mm particle size	86 %	84 %	85 %
Percentage removal efficiency for 0.004mm particle size	93 %	91 %	90 %
Percentage removal efficiency for particle size of 0.006mm	97 %	97 %	96 %
Percent removal efficiency for particle size of 0.01mm	99 %	99 %	97 %

Table 4
Comparing the design parameters obtained in the literature with the ones obtained in the present study.

Parameters	Unit of measurement	Value	Calculated Value
Cyclone diameter (Dc)	m	<1.0	0,3024521
Pressure drop	Pa	<2488.16	224
Velocity ratio (Vi/Vs)		<1.35.	0,662802911
Inlet velocity	m/s	15.2–27.4	22

3.3. CAE simulation stage

In this section, the static and dynamic analyses of the proposed cyclone separator design are carried out by means of simulations.

It should be noted that in this case, two base materials were considered for the design of the Stairmand cyclone, stainless steel and a black steel sheet, considering the future economic viability of the implementation of the particle separator system. Fig. 6 shows the Stairmand cyclone separator in two possible materials of construction.

For this purpose, a wind pressure of 35.07 Pa at the inlet of the flow was considered. This was calculated from design parameters such as the gas density (air = 0.14kg/m^3), the density of the generated particulate matter (1,740g/cm^3), the gas inlet velocity (22 m/s) and the technical data of the extraction motor. Fig. 7 shows the simulation results for both types of materials performed in SolidWorks®.

In particular, the force study highlights that the gas outlet tube experiences the most significant impact during the inlet flow.

Examining the results shown in Fig. 7, it is evident that both outlet tubes effectively resist the pressure exerted by the inlet flow. Although the stainless steel has a lower stress-induced deformation (1085 Pa) compared to the 4146 Pa of the black sheet, these values are considered negligible for system operation (Table 5).

In relation to the minimum and maximum static displacements (Table 5) of the designed part in each of the materials, it can be observed that although the tube designed in black sheet has a higher value (1.237 $\times$ 10^{-6}), this does not compromise the operational integrity of the designed separator.

Because the flow path and velocity change are critical to understanding the fluid dynamics and performance characteristics of the cyclone separator, SolidWorks® Flow Simulation was then performed on each of the materials used in the Stairmand cyclone design (Fig. 8).

Here, the changes are reflected in the color chart, where the dark blue color is the minimum velocity that occurs in the designed cyclone separator and the red color is the maximum velocity that the flow reaches in the separator. It can be seen that the gas trajectory includes a double vortex, with the maximum velocity in the gas inlet area being similar for the two cyclones designed, reaching 29.7 m/s and 28.8 m/s for the stainless steel and black steel sheets, respectively. In addition, as

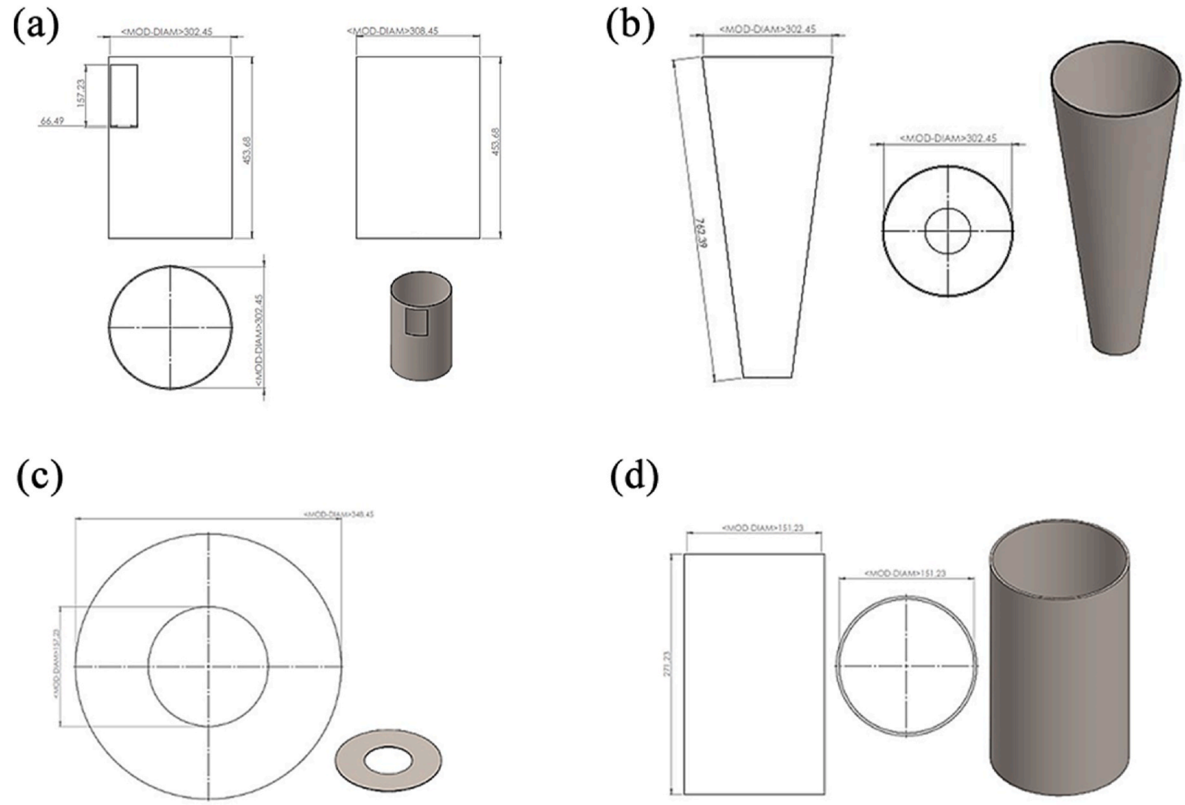

Fig 5. CAD design of the Stairmand cyclone components (a) base, (b) cone, (c) cover, and (d) discharge pipe.

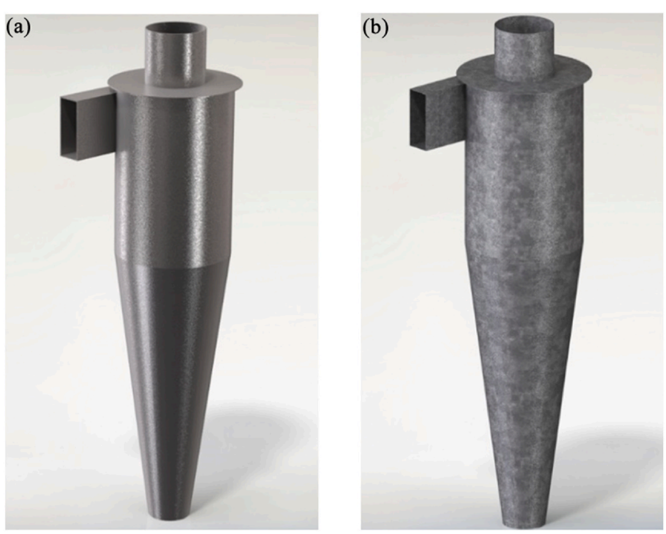

Fig 6. Stairmand cyclone separator designed in (a) stainless steel and (b) black steel sheet.

expected, the velocity of the gas decreases as it enters the cyclone, allowing heavier particles to be affected by centrifugal forces.

Finally, to determine the number of particles released into the air per second and those collected as particulate matter, a flow analysis was performed for particles of different diameters (1, 2.5, 4, 6 and 10 μm) and at different critical velocities. This means that the inlet velocity is 0 m/s and the maximum velocity for a cyclone as reported in the literature is 27.4 m/s as well as the ideal inlet velocity for the design of the prototype is 22 m/s.

In this case, Fig. 9 shows only the trajectories of the 1 and 10 μm particles at a constant inlet velocity of 22 m/s. For comparison, Table 6 shows all simulation conditions for the two materials used in the Stairmand cyclone design.

Again, a higher velocity is observed at the inlet of the system and its decrease inside the cyclone. In addition, as is well known, the vortex generates centrifugal forces at each point inside the cyclone, so that the discrete phase (particulate material), being heavier than the continuous phase (gas), begins to separate and move towards the walls of the cyclone [15,31]. In this sense, in Fig. 9(b) and (d), corresponding to the simulation with particles of 10 μm, a displacement of the same towards the walls is observed, contrary to what happens with the particles of 1 μm, where they remain suspended in the center of the cyclone.

On the other hand, the particles inside the cyclone, under the influence of the axial velocity, descend to the bottom of the cyclone where they are collected. And the clean air is expected to swirl upward and leave the cyclone through the top outlet. However, for the design parameters, it is observed that in the simulations with particles smaller than 4 μm an amount between 33 and 54 particles per second are expelled from the top, while between 71 and 50 are directed to the collector, for the different velocities studied.

In the case of larger particles, 6 μm, the number of particles expelled with the air decreases considerably, obtaining values of 5 and 8 particles per second for the cyclones made of stainless steel and black sheet steel, respectively. Finally, in the simulation with particles of 10 μm, the number of particles expelled with the air is completely eliminated, but the number of particles directed to the collector also presents a drastic decrease, obtaining values of 12 and 14 particles per second for the cyclones designed in stainless steel and black steel sheet, respectively.

The analysis of flow paths, velocity variations, and particle sizes enabled an accurate assessment of the cyclone separator's efficiency in the Fique sack production process. The separator demonstrated high performance across various particle sizes, achieving efficiencies from 66 % for 1 μm particles to 99 % for 10 μm particles, with an average efficiency of 88 % for particles between 1 and 10 μm. This performance compares favorably with recent literature across various industries. For

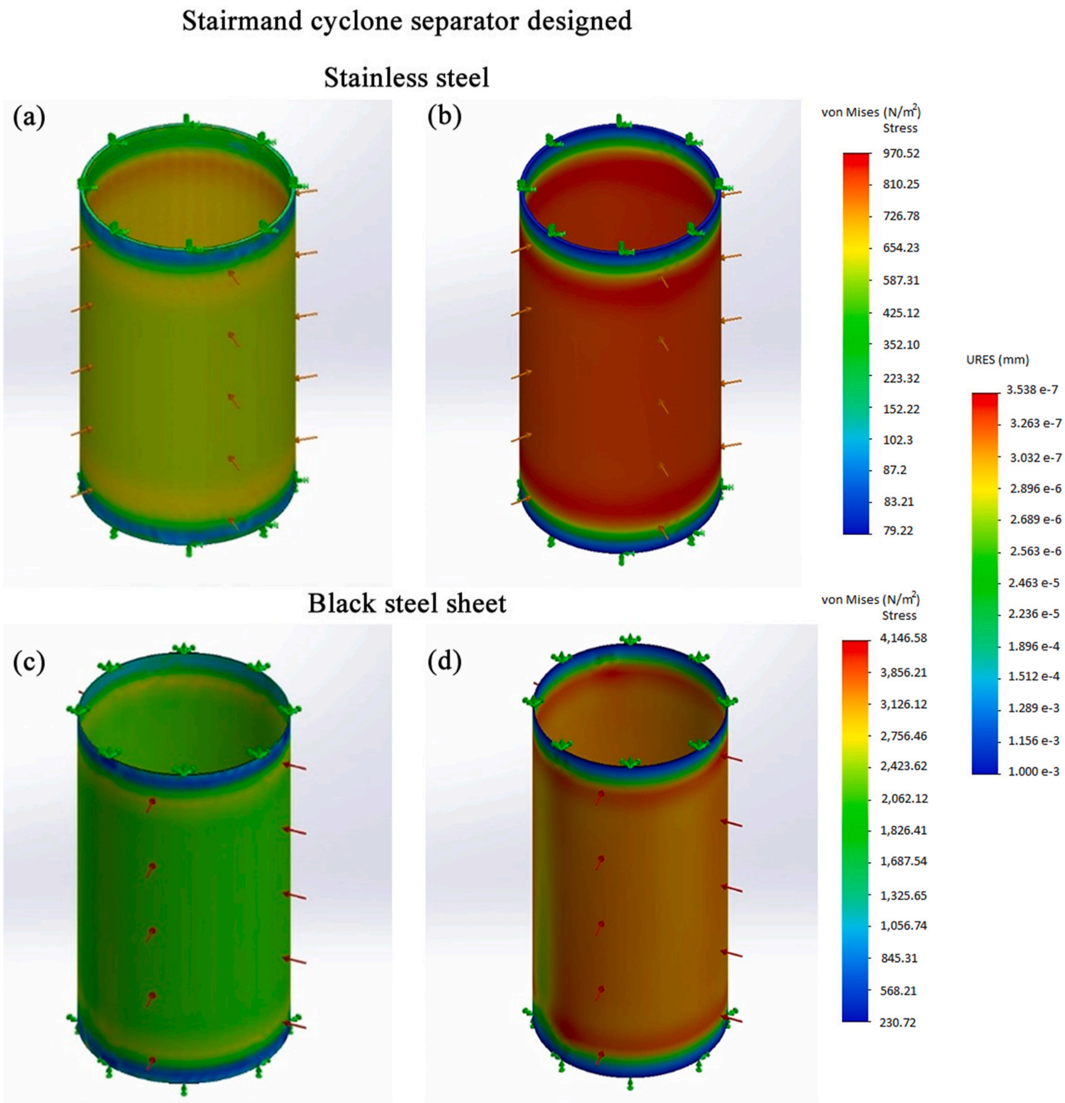

Fig 7. Static simulation of the Stairmand cyclone showing (a) static stress and (b) displacement of the gas outlet pipe in stainless steel; (c) static stress and (d) displacement of the gas outlet pipe in black steel sheet.

Table 5
Comparison of static simulation data in terms of maximum and minimum values of stress and displacement in the gas outlet pipe designed in different materials.

Stress (N/m^2)	Stainless steel gas outlet pipe	Gas outlet pipe in black sheet
Stress minimum	79.22	230.7
Stress maximum	1085	4146
Displacement (mm)		
Minimum static displacement	1.000×10^{-3}	1.000×10^{-3}
Maximum Static displacement	3.538×10^{-7}	1.237×10^{-6}

instance, Vaitiekūnas et al. reported 69 % efficiency for 10 μm glass particles [32], while Fu et al. achieved 89.9 % overall efficiency for PM2.5 in the methanol-to-olefin industry [33]. Kim et al. reported 80–99 % efficiency for manufacturing industries [34], and Sylvia et al. achieved 98 % efficiency for PM2.5 in palm oil mills [35]. Notably, the Fique sack cyclone's performance for smaller particles (66 % for 1 μm) surpasses the 39.9 % efficiency reported by Fu et al. for a standard cyclone without droplets [33]. These comparisons demonstrate that the cyclone design for Fique sack production is effective and competitive for particulate matter control, balancing efficiency and practicality.

On the other hand, the economic feasibility of the cyclone separator adapted to the particularities of the production process of the case study in the company Empaques del Cauca S.A., presents an economic item associated with its implementation of $ 4214.60 USD where the items related to materials and supplies, human talent, construction and related technical services are involved, a 39 % cheaper cost compared to the commercial value of these conventional systems for the control of particulate matter estimated at $ 5460 USD.

The results of this study have important practical implications for Empaques del Cauca S.A. and other similar industries in the manufacturing sector. Implementing the designed Stairmand cyclone separator offers a viable solution to comply with environmental regulations (NTC5517) that require particle extraction systems in manufacturing facilities. By achieving an average separation efficiency of up to 88 % for particles between 1 and 10 μm, the cyclone separator can significantly reduce particulate emissions, thereby reducing the environmental impact on surrounding residential areas. In addition, the improved air quality within the manufacturing facility is expected to reduce the incidence of acute respiratory infections among workers, thereby improving occupational health and safety. At the same time,

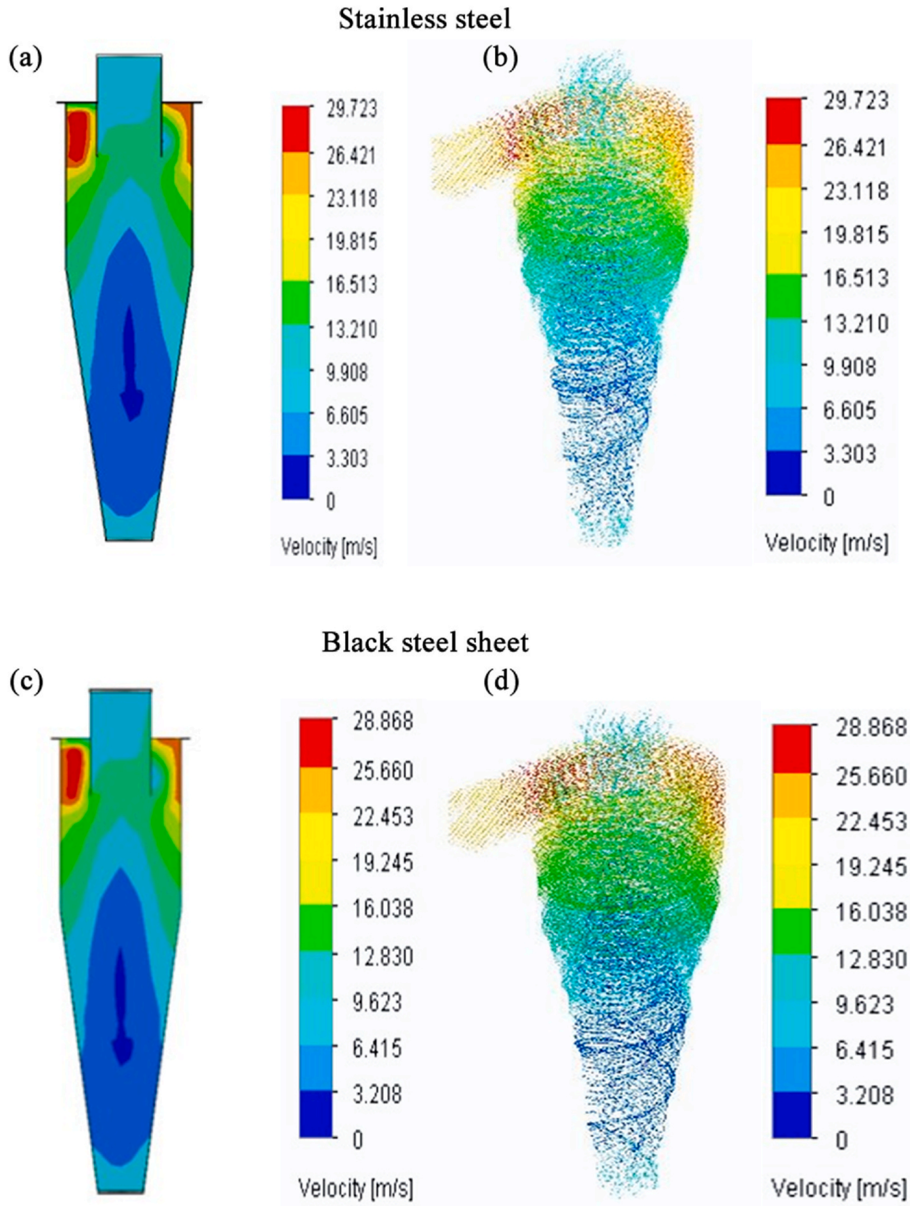

Fig 8. Dynamical simulation of the Stairmand cyclone showing (a) flow path and (b) velocity change for the cyclone separator designed in stainless steel and (c) flow path and (d) velocity change for the cyclone separator designed in black steel sheet.

reducing suspended particulate matter is expected to minimize machine fouling, potentially resulting in improved operational efficiency and reduced maintenance requirements. Thus, this study represents a significant step towards sustainable development in the fique bag production industry, balancing economic interests with environmental and social responsibilities.

4. Conclusions

The results of this study provide valuable information on the performance and design considerations of the Stairmand type cyclone separator to be implemented at Empaques del Cauca S.A., in this sense it can be said that.

- The design, simulation, and implementation of the cyclone separator for treating particulate matter in fique bag production at Empaques del Cauca S.A. successfully met the functional, technical, and operational requirements established by engineering professionals. The separator achieved separation efficiencies of 66 % for 1 μm particles, 86 % for 2.5 μm, 93 % for 4 μm, 97 % for 6 μm, and 99 % for 10 μm particles.
- The static studies of displacement and stress in the cyclone separator's outlet pipe revealed a maximum static displacement of 3.538×10^{-7} mm and a maximum stress of 1085 N/m^2. These results identified stainless steel as the superior material over black steel sheet for cyclone construction, demonstrating better performance with a maximum speed limit of 29.723 m/s.
- The two proposed materials for the cyclone separator demonstrated satisfactory performance for PM10, expelling 0 particles per second into the air and collecting 12 particles per second in the condenser at velocity profiles of 0 m/s, 22 m/s, and 27.4 m/s. The stainless-steel design showed increased collection, capturing 14 particles per second in the condenser at 22 m/s and 27.4 m/s compared to the black sheet design.
- The proposed Stairmand cyclone separator offers a practical solution for Empaques del Cauca S.A. and similar industries, achieving an

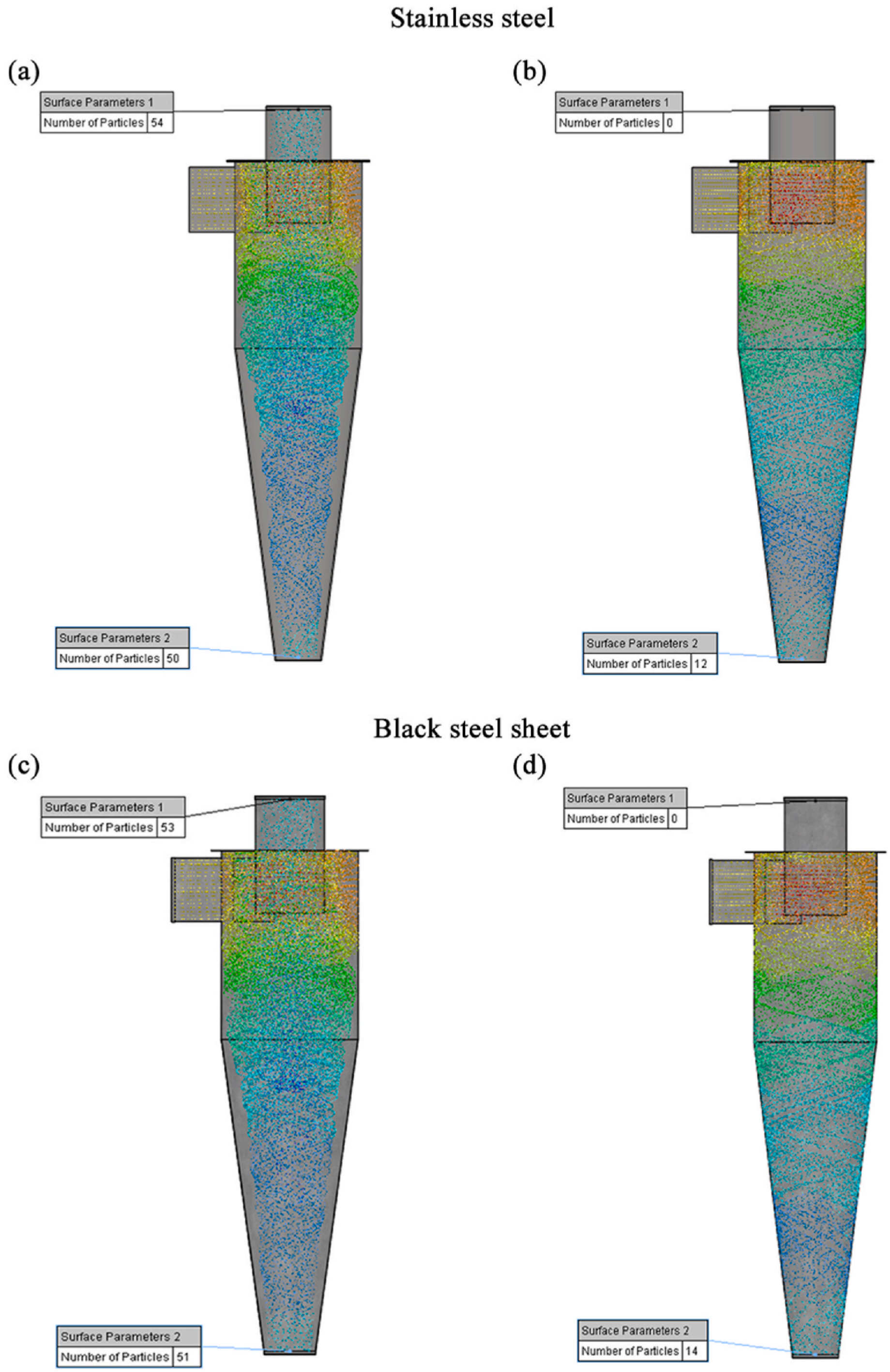

Fig 9. Dynamical simulation of the Stairmand cyclone showing the trajectory of the expelled particles, (a)–(c) 1μm and (b)–(d) 10 μm, through the cyclone separator designed in the two different materials.

appropriate particle separation efficiency in compliance with environmental regulations, which can lead to improved worker health and safety, and potentially increase operational efficiency, contributing to sustainable development in the production of fique bag.

CRediT authorship contribution statement

Johana Astudillo Gutierrez: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Jhon Alexander Guerrero Narvaez:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Diego Andres Campo Ceballos:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Javier Andres Muñoz Chaves:** Writing – review & editing, Writing – original draft, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 6
Comparison of the number of particles expelled by the cyclone separator designed in two different materials.

Particle size and velocity	Stainless steel cyclone separator		Cyclone separator in black steel sheet	
	Particles ejected per second into the air	Particles ejected per second to the collector	Particles ejected per second into the air	Particles ejected per second to the collector
1 µm - 0 m/s	54	50	53	51
1 µm - 22 m/s	54	50	53	51
1 µm - 27,4 m/s	54	50	53	51
2.5 µm - 0 m/s	51	53	48	56
2.5 µm - 22 m/s	51	53	48	56
2.5 µm - 27,4 m/s	51	53	48	56
4 µm - 0 m/s	33	71	31	73
4 µm - 22 m/s	33	71	31	73
4 µm - 27,4 m/s	33	71	31	73
6 µm - 0 m/s	6	66	8	64
6 µm - 22 m/s	5	68	8	67
6 µm - 27,4 m/s	5	66	8	66
10 µm - 0 m/s	0	12	0	12
10 µm - 22 m/s	0	12	0	14
10 µm - 27,4 m/s	0	12	0	14

Data availability

Data will be made available on request.

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