https://doi.org/10.1590/jatm.v17.1386
THEMATIC SECTION | AIR TRANSPORTATION SYSTEMS: INFRASTRUCTURE, OPERATIONS, AND ENVIRONMENTAL INTEGRATION

Risk Analysis of Fireworks Balloons in Brazilian Airspace

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ABSTRACT

This study assesses the aviation safety risks in Brazil posed by fireworks balloons, a cultural practice that has become a significant concern for air operations. The methodology involved analyzing Centro de Investigação e Prevenção de Acidentes Aeronáuticos (CENIPA) data on notifications and recorded collisions from 2014 to 2023, using descriptive and statistical approaches, alongside the application of the Federal Aviation Administration (FAA) risk matrix to assess the probability and severity of collisions. The results reveal a high concentration of notifications in the states of São Paulo, Rio de Janeiro, and Paraná, with a focus on the airports of Guarulhos (SBGR), Galeão (SBGL), Santos Dumont (SBRJ), Curitiba, Viracopos (SBKP), Congonhas (SBSP), and Campo de Marte (SBMT). The final risk analysis indicated that SBGR and SBGL airports present the highest collision risks, while SBRJ, despite not recording collisions, requires attention due to the high number of notifications. Additionally, SBKP and SBSP showed moderate risks, and SBMT, assessed using the general aviation risk matrix, exhibited a high risk for smaller aircraft. Pearson's correlation (0.9157) between the number of notifications and collisions suggests that increased notifications are associated with a higher risk of collision. The study concludes with an urgent call for stricter regulations and preventive measures, emphasizing the need for new technologies to mitigate risks to Brazilian airspace.

Keywords: Risk assessment; Fireworks; Balloons; Flight safety; Aviation.

INTRODUCTION

Portuguese colonization introduced European cultural elements to Brazil starting in the 16th century. According to Fernandes (2023), the Catholic Church assimilated these elements, replacing pagan rituals with tributes to saints. These European traditions merged with Indigenous and African influences. The release of balloons, incorporated into festivities, symbolizes prayers to saints (Rangel 2008). Over time, this cultural practice began to share airspace with aircraft, becoming an increasing concern for authorities and airspace operators.

Fireworks and balloons can significantly impact air quality and airspace safety. Fireworks events lead to substantial increases in particulate matter concentrations, especially fine and ultrafine particles, as well as elevated levels of trace metals and ions (Lin 2016; Thakur *et al.* 2010; Zhang *et al.* 2017). These pollutants can persist in the air for extended periods, potentially causing adverse health effects (Hoyos *et al.* 2019; Liu *et al.* 1997). Fireworks also generate noise from aerial bursts, with peak overpressures reaching up to 15 psf (Maglieri and Henderson 1973).

Received: Feb. 22, 2025 | **Accepted:** Apr. 29, 2025
Peer Review History: Single Blind Peer Review.
Section editor: Leonardo Marini-Pereira

Several cultures worldwide incorporate the use of balloons or lanterns in traditional celebrations, often imbued with profound symbolic meanings. In Thailand, the Lantern Festival (Yi Peng) involves releasing thousands of paper lanterns into the sky, symbolizing the letting go of past troubles and welcoming a prosperous future (Thaizer 2025). Similarly, in China, the Lantern Festival marks the end of Chinese New Year celebrations, featuring illuminated lanterns representing hope and spiritual enlightenment. India's Diwali, or "Festival of Lights," also involves lanterns and fireworks symbolizing the triumph of light over darkness. In Mexico, particularly in Michoacán, "Globos de Cantoya" – paper lanterns – are launched during local festivities as tributes to patron saints.

However, due to environmental risks and air safety concerns associated with these practices, various countries have adopted specific regulations to mitigate negative impacts. In Brazil, legislation strictly prohibits balloon releases, considering their proven risks of fires and aviation accidents. Conversely, in Thailand, while the Lantern Festival remains permitted, there is increasing scrutiny over its environmental and safety impacts, prompting regulatory measures aimed at balancing cultural preservation and public safety through education and awareness campaigns. Portugal offers another regulatory approach, notably during the São João festivities in Porto, where the traditional launching of hot air balloons is subject to strict limitations on timing and designated locations due to air safety concerns (SIC Notícias 2024).

In Brazil, large artistic hot air balloons have posed fire and collision risks, leading to their criminalization (Cruz 2021). To address these challenges, some regions are implementing stricter environmental legislation and exploring the integration of unmanned free balloons into airspace management systems (Hegyi and Jósvai 2019; Lin 2016). These efforts aim to mitigate the environmental and safety impacts of fireworks and balloons in airspace.

Despite their association with small, simple, and seemingly harmless *balões juninos*, fireworks balloons frequently spotted in Brazilian airspace can range from 15 to 30 meters in size, according to the Guidance Manual of the Civil Aviation Secretariat (SAC). There are records of free balloons reaching up to 100 meters in length, capable of carrying massive flags, banners, streamers, and structures containing dozens of kilograms of explosives. One such case was recorded in 2013 involving a combustion charge weighing 195 kg (Brasil 2016).

The increasing number of reports of fireworks balloons sighted near airport facilities reflects the frequent occurrence of incidents. One such event occurred on May 14, 2023, when a burning balloon fell onto an aircraft parked during refueling at Santos Dumont Airport (SBRJ) (Monteiro 2023). Another serious incident occurred on June 17, 2011, when an Airbus A319 collided with an advertising banner suspended by a balloon, compromising its automatic systems, the pitot tube, and the total air temperature (TAT) sensor. This forced the crew to continue the flight under a condition known as unreliable speed, meaning the aircraft's speed readings were unreliable (Centro de Investigação e Prevenção de Acidentes Aeronáuticos (CENIPA 2013).

Considering the average altitude of these balloons (10,000 feet) and the typical speed of aircraft (ranging from 150 to 250 knots, equivalent to 270 to 450 km/h), along with the weight of the obstacle, a collision could generate an impact force of approximately 2.26 tons for a 10-kilogram balloon and up to 100 tons for a 50-kilogram balloon (CENIPA 2013).

On May 7, 2023, air traffic control (ATC) alerted the pilot of an Embraer E195 jet about a balloon carrying a banner that had fallen near runway threshold 20L at SBRJ. On the same day, Viracopos International Airport (SBKP) was closed for 9 minutes due to the presence of seven balloons in the vicinity, two of which fell within airport grounds (Basseto 2023a). Six days earlier, balloons carrying banners were projected over runway threshold 33 and reported to the control tower (Basseto 2023b). In January 2023, fireworks balloons were launched near runway threshold 15, with one reaching the intersection of taxiways C and H (Basseto 2023c). Such incidents are common in the Southeast and South regions, with São Paulo and Rio de Janeiro accounting for 81.29% of reported occurrences.

According to CENIPA (2024), more than 900 reports of balloons in air routes have been recorded in Brazil. With the expansion of air transport, which is essential in many regions, it is imperative to enhance studies on this issue. The introduction of new technologies, such as drones and electric vertical takeoff and landing (eVTOLs), further increases the need to understand the risks posed by fireworks balloons (EASA 2021; Haddad *et al.* 2020), which primarily impact landing and takeoff operations (Federal Aviation Administration 2003).

One of the motivations for this study is the downgrade of Brazilian airspace safety classification by the International Federation of Air Line Pilots' Associations (IFALPA) in April 2016 (IFALPA 2016). IFALPA categorizes aerodromes and airspace into three levels: deficient, critically deficient (black star), and special category. Due to the frequent sightings of balloons and pilot reports, Brazilian airspace was classified as critically deficient, a designation comparable to war zones, which increases operational costs (AERO Magazine 2016; Schmitt 2018).

Within this framework, there is a broad consensus that the risk of collisions with aircraft has been a significant concern, including for international aviation authorities. Therefore, this study aims to assess the risk of collisions involving fireworks balloons in airport operations.

BALLOON-RELATED RISK AND THE LEGAL FRAMEWORK IN BRAZIL

The illegal practice of launching fireworks balloons in Brazil poses significant risks to aviation safety (Boynard 2018; Schmitt 2018). These balloons, reaching up to 105 meters in length and often carrying fireworks or lanterns, threaten air traffic and have contributed to the downgrade of Brazilian airspace safety classification (Cruz 2021; Schmitt 2018).

The *baloeira* tradition, which originated in Catholic festivities, has evolved into a secular art form and an emergent technology (Cruz 2021). Despite its criminalization, thousands of balloons are launched annually, increasing the risk of collisions and aircraft damage (Boynard 2018; Cruz 2021). This issue calls for greater awareness and preventive measures to mitigate the associated risks (Boynard 2018; Schmitt 2018).

A collision between an aircraft and a balloon, which can weigh hundreds of kilograms when considering its structure and payload, can have catastrophic effects. Even so-called eco-friendly balloons, which do not use fire, pose a significant risk to aviation due to their uncontrollable trajectory, invisibility to radar systems, and inability to be intercepted mid-flight. Additionally, unmanned balloons can lead to unplanned changes in air traffic routes, compromising flight punctuality, causing substantial economic losses, and degrading the quality of services provided to passengers (CRCEA-SE 2024).

The danger posed by balloons is not limited to airspace operations. Their presence at airports can represent a direct threat to operational areas, where there is a high concentration of aircraft, passengers, fuel, and flammable materials. Beyond the civil aviation sector, unmanned balloons can cause wildfires and urban fires, short circuits in power transmission lines, fires at refineries, and other hazards to critical infrastructure, ultimately endangering public safety as a whole.

In Brazil, since December 7, 1940, Article 261 of the Penal Code has established a penalty of 2 to 5 years for those who endanger or obstruct air navigation, and up to 12 years in cases involving the destruction or crash of an aircraft (Brasil 1940). In 1998, Law No. 9605 introduced criminal sanctions for actions harmful to the environment, imposing fines and/or up to 3 years of imprisonment for individuals who manufacture, sell, transport, or launch fireworks balloons (Brasil 1998).

Additionally, the Penal Code, in Article 163, stipulates fines and/or imprisonment of one to 6 months for property damage, while Article 129 prescribes a sentence of 3 to 12 months for bodily harm, which may increase to 14 years in cases of injury resulting in death (Brasil 2016).

The balloon-related risk is exacerbated by the fact that balloon releases are not limited to the June and July festive period but occur throughout the year. Recent incidents recorded at high-demand airports highlight the need for continuous enforcement actions and awareness campaigns to mitigate their impact on aviation (SNA 2024). The campaign promoted by the Sindicato Nacional dos Aeronautas (SNA) emphasizes the importance of reporting balloon sightings, stressing that their presence in airspace directly threatens the safety of thousands of people.

Given this scenario, the Department of Airspace Control (Departamento de Controle do Espaço Aéreo [DECEA]), an entity under the Aeronautics Command (Comando da Aeronáutica [COMAER]), has established regulations to reduce the risks associated with balloon releases. In November 2016, the second amendment to Instrução do Comando da Aeronáutica 100-12 (ICA 100-12) came into effect (Brasil 2016) in compliance with the recommendations of the International Civil Aviation Organization (ICAO). This regulation was developed by DECEA, an agency under the COMAER, to align the Rules of the Air with the Convention on International Civil Aviation (CICA).

Regarding fireworks balloons, ICA 100-12 defines them as lighter-than-air aircraft, and its Annex B categorizes them as follows:

- Light: when the combined payload weighs less than 4 kg.
- Medium: when the payload consists of two or more packages, with a total weight between 4 and 6 kg.
- Heavy: when the combined payload exceeds 6 kg, including at least one package weighing 3 kg or more and another exceeding 2 kg, with an area density greater than 13 g/cm³. Additionally, these balloons must be equipped with a rope or suspension device capable of withstanding a force of 230 newtons or more (Brasil 2013).

ICA 100-12 prohibits the release of balloons without prior approval from DECEA, which must be requested from the responsible State during the flight planning phase. Approval may be granted for a series of flights or for periodic launches, such as atmospheric research balloons. The operation of free balloons is strictly prohibited when there is a risk of collision with the surface or a potential hazard to people or property (Brasil 2013).

The regulation also establishes operational limitations, mandatory equipment requirements, and guidelines for flight termination procedures. After launching medium or heavy fireworks balloons, the operator must notify the ATC authority with the flight identification, launch location and time, and estimated cruising altitude of up to 18,000 meters. Heavy balloons operating up to 60,000 feet must have position reports recorded every 2 hours (Brasil 2013).

This study is motivated by the need for studies and the existing gaps regarding the risks posed by fireworks balloons in airport operations. The current literature generally highlights the hazards associated with such occurrences. Although most sightings do not directly impact flight operations, balloons' uncontrollability increases the likelihood of collisions. Despite their low density, these objects can cause accidents due to the high aircraft speeds at the flight levels where balloons are typically found (CENIPA 2013).

RISK ANALYSIS OF FIREWORKS BALLOONS IN BRAZIL

Database

The scarcity of studies on the risk of balloon-aircraft collisions motivated the search for data in regulatory literature. Factors such as the location of occurrences, flight phase, and balloon characteristics were analyzed using incident report forms from CENIPA (2024), which are completed by citizens who observe balloons along aircraft flight paths.

The dataset includes variables such as sky conditions and the effects on flight operations. The analysis was conducted within a defined temporal range (2014–2023) and spatial framework.

Temporal delimitation

Despite the possibility of multiple reports of the same balloon by different observers, each event was considered unique due to its distinct implications for both airspace and ground operations. In cases involving collisions, duplicate reports were consolidated into a single event, while erroneous or redundant records were excluded.

Thus, occurrences from the CENIPA database covering the period from 2014 to 2023 were tabulated. Table 1 presents the compiled data, including the airports involved, impacted aircraft components, phase of operation, altitude (in feet), and the number of reported occurrences.

Spatial delimitation

Data from the entire national territory were considered, both for reported occurrences and for measuring flight volumes in Brazil and its regional segments. However, the analysis was limited to the main airports in Rio de Janeiro and São Paulo.

According to the Supply and Demand Report (ANAC 2023), it was possible to estimate the total number of commercial aviation departures, including domestic and international flights, as presented in Table 2. Additionally, the annual number of reports of fireworks balloons and recorded collisions, as documented by CENIPA (2024), was also included in this table.

Table 1. Collisions of fireworks balloons with aircraft.

Year	ICAO	Impacted part(s)	Flight phase	Altitude (ft)	Occurrences
2014	SBCT	Wing/rotor	Descent	5,500	1
		Wing/rotor	Final approach	5,500	1
	SBSP	Wing/rotor	Final approach	-	1
	SBGL	Fuselage	Movement area	Ground	2
	SBGR	Nose	Takeoff	200	2
		Engine No. 1	Landing	-	1
2015	SBGR	Wing/rotor	Movement area	Ground	3
	SBBU	Radome	Cruise	35,000	1
2016	SBGL	Engine No. 2	Takeoff	Ground	1
	SBKP	Fuselage	Final approach	2,500	2
2017	SBGR	Fuselage	Climb	7,000	2
	SBSP	Runway	-	Ground	1
2018	SBGR	Engine No. 1	STAR	2,000	1
		Fuselage and tail	Final approach	5,000	1
	SBMT	Other	Other	2,370	1
2019	SBCT	Fuselage, wing/rotor	Movement area	Ground	1
	SBGL	Landing gear	Landing	-	1
2020	SBGR	Fuselage	Movement area	Ground	1
2021	-	-	-	-	0
2022	SBGR	Fuselage, wing/rotor, and tail	Movement area	Ground	1
2023	SBGR	Engine No. 2	Landing	500	1

Source: CENIPA (2014-2023).

Table 2. Number of flights in Brazil.

Year	Domestic flights	International flights	Total flights	Number of reports	Number of collisions
2014	941,531	135,235	1,076,766	320	8
2015	935,654	136,021	1,071,675	310	4
2016	828,882	126,939	955,821	481	3
2017	805,459	126,803	932,262	717	3
2018	816,009	142,593	958,602	915	3
2019	802,417	137,248	939,665	933	2
2020	406,234	539,99	460,233	592	1
2021	546,540	47,713	594,253	883	0
2022	730,685	93,986	824,671	903	1
2023	789,286	122,040	911,326	836	1
2014–2023	7,602,697	1,122,577	8,725,274	6,890	26

Source: ANAC (2014–2023) and CENIPA (2024), adapted by the authors.

Data processing and analysis

According to Lobianco (2012), in order to standardize the calculation of individual indicators (I), the criteria for operational movements defined in Circular Normativa de Tráfego Aéreo (CIRTRAF) 100-25 (COMAER 2004) were adopted. The total number of movements was multiplied by 100,000 aircraft operations for each calendar year. The calculation of the I is dimensionless and is given by Eq. 1:

$$I = \frac{i}{n} \text{ x } 100{,}00 \tag{1}$$

where i is the number of events in a given period and n is the total number of flights in the same period.

The probability of an event is calculated as the ratio between the number of favorable cases (presence of a balloon) and the number of possible cases (collision events). The recommendations of the Safety Risk Management Policy, Order 8040.4B (FAA 2017) were applied to develop a risk analysis that best aligns with the collected data. This policy classifies accident occurrences based on both qualitative and quantitative probability measures.

Due to the differences across aviation system segments (e.g., commercial aviation versus general aviation), the FAA provides distinct probability definitions for commercial operations (Table 3) and general aviation operations (Table 4). However, the same severity definitions (Table 5) are applied to both categories.

Table 3. Probability for commercial operations/large transport category.

Category	Probability	Qualitative	Quantitative
A	Frequent	Expected to occur routinely	Expected to occur more than 10 times per year
B	Probable	Expected to occur repeatedly	Expected to occur between one and 10 times per year
C	Remote	Expected to occur occasionally	Expected to occur once every 1 to 3 years
D	Extremely remote	Expected to occur rarely	Expected to occur once every 3 to 10 years
E	Extremely improbable	Unlikely to occur, but not impossible	Expected to occur less than once every 10 years

Source: FAA (2017), adapted by the authors.

Table 4. Probability for general aviation/small aircraft and rotorcraft.

Category	Probability	Qualitative	Quantitative
A	Frequent	Expected to occur routinely	Expected to occur more than 100 times per year (or more than approximately 10 times per month)
B	Probable	Expected to occur repeatedly	Expected to occur between 10 and 100 times per year (or approximately one-10 times per month)
C	Remote	Expected to occur occasionally	Expected to occur once every 1 month to 1 year
D	Extremely remote	Expected to occur rarely	Expected to occur once every 1 to 10 years
E	Extremely improbable	Unlikely to occur, but not impossible	Expected to occur less than once every 10 years

Source: FAA (2017), adapted by the authors.

Table 5. Severity definitions.

	2	3	4	5
Catastrophic	**Hazardous**	**Major**	**Minor**	**Minimal**
Multiple fatalities (or fatality of all onboard), usually resulting in the loss	Multiple serious injuries; fatal injury to a relatively small number of people (one or two); or total hull loss without fatalities and/or fires.	Physical harm or injuries to people; aircraft parts impacted; evasive maneuvering actions; go-arounds or aborted takeoffs.	Physical discomfort for individuals; temporary airport closures and/or temporarily interrupted operations.	Insignificant effect on safety; airport alert without operational interruptions.

Source: FAA (2017), adapted by the authors.

It is also emphasized that when developing specific probability definitions, the number of aircraft operating within notification areas or the size of the system under analysis (such as a state or an airport) should be taken into account. Additionally, it is essential to ensure that these definitions align with the qualitative classifications listed in the aforementioned tables.

A risk matrix is a graphical method used to represent safety risk, with columns reflecting severity categories and rows representing probability categories. The FAA employs different risk matrices for various operational segments. Figure 1a addresses large transport commercial operations, while Fig. 1b focuses on general aviation, which applies to airports such as Bauru (SBBU) and Campo de Marte (SBMT). This differentiation facilitates risk assessment by considering the specific characteristics of each segment.

(a)

Severity / Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	[Green]	[Yellow]	[Red]	[Red]	[Red]
Probable B	[Green]	[Yellow]	[Red]	[Red]	[Red]
Remote C	[Green]	[Yellow]	[Yellow]	[Red]	[Red]
Extremely remote D	[Green]	[Green]	[Yellow]	[Yellow]	[Red]
Extremely improbable E	[Green]	[Green]	[Green]	[Yellow]	[Red] * [Yellow]

(b)

Severity / Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	[Green]	[Yellow]	[Red]	[Red]	[Red]
Probable B	[Green]	[Yellow]	[Yellow]	[Red]	[Red]
Remote C	[Green]	[Green]	[Yellow]	[Yellow]	[Red]
Extremely remote D	[Green]	[Green]	[Green]	[Yellow]	[Red] * [Yellow]
Extremely improbable E	[Green]	[Green]	[Green]	[Green]	[Yellow]

Source: FAA (2017).

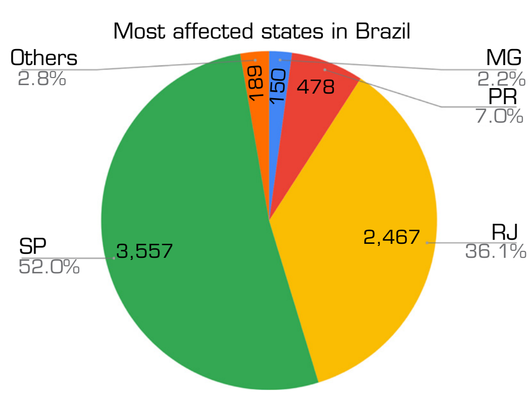
Figure 1. (a) Risk matrix for commercial operations/large transport category; (b) Risk matrix for general aviation/small aircraft and rotorcraft.

High risk (red) requires mitigation, monitoring, and high-level approval; it is temporarily acceptable while control measures are implemented. Medium risk (yellow) is acceptable with monitoring, and mitigation is recommended but not mandatory. Low risk (green) is acceptable without restrictions, requiring only documentation if assessed. The tables also indicate that there may be an association between common or isolated causes of medium and high risks.

RESULTS AND DISCUSSION

Descriptive data analysis

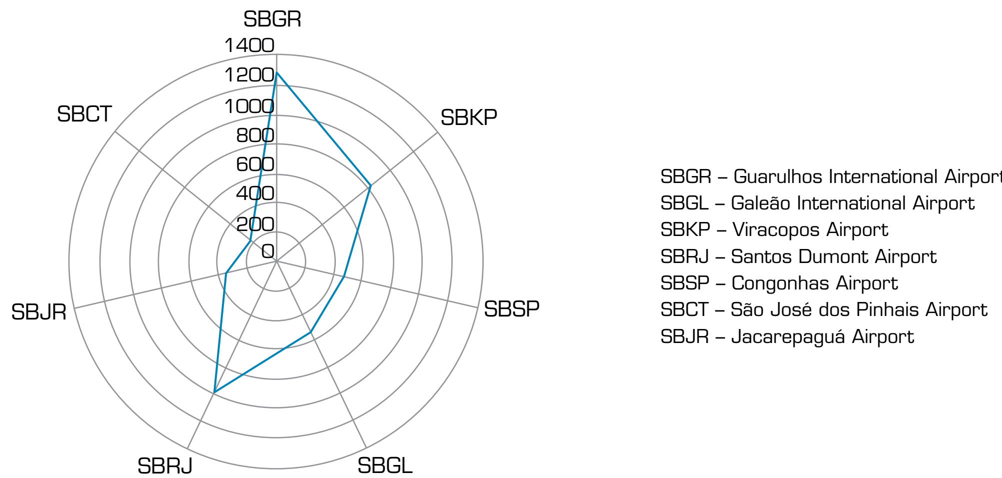
The descriptive analysis identified the main states in Brazil with the highest number of reports. Based on the processing of data from unmanned balloon incident reports from 2014 to 2023, it is inferred that most records originate from the state of São Paulo, with 3,557 reports, accounting for 52% of the total; Rio de Janeiro, with 2,467 reports, representing 36.10%; and Paraná, with 478 reports, approximately 7% of the total. These three states account for nearly 95% of all notifications, as shown in Fig. 2.



Source: Elaborated by the authors.

Figure 2. Reports from the most affected states in Brazil (MG = Minas Gerais; PR = Paraná; RJ = Rio de Janeiro; SP = São Paulo).

Figure 3 presents the main airports (in the states of São Paulo and Rio de Janeiro) on the y-axis, categorized by the number of reports on the x-axis.

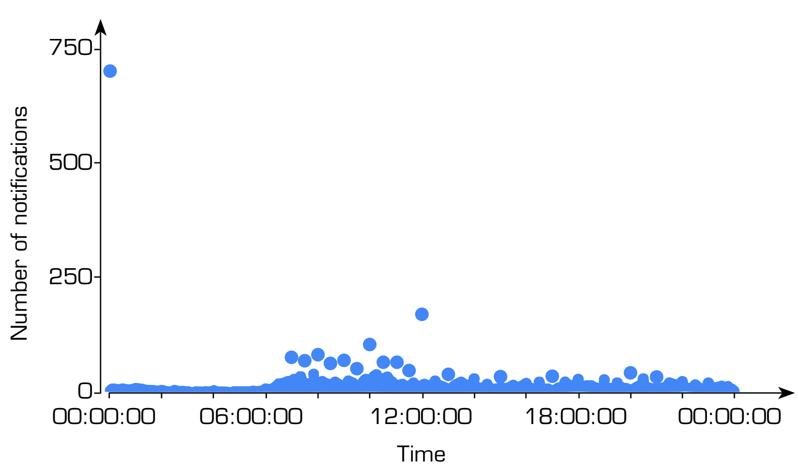


Source: Elaborated by the authors.

Figure 3. Reports of fireworks balloons.

The radar chart illustrates the number of balloon sighting notifications across different airports, highlighting distinct regional variations. Guarulhos International Airport (SBGR) recorded the highest number of sightings, with 1,275 notifications, indicating a significant concentration of unauthorized balloon activity. Galeão International Airport (SBGL) and Viracopos Airport (SBKL) follow with 994 and 825 reports, respectively, reinforcing the prevalence of this issue in major aviation hubs. Moderate levels of sightings, ranging between 200 and 500 notifications, were observed at other critical airports, including Santos Dumont Airport (SBRJ), Congonhas Airport (SBSP), São José dos Pinhais Airport (SBCT), and Jacarepaguá Airport (SBJR), suggesting either lower balloon activity or less frequent detection and reporting.

A significant portion of the reports is concentrated in the morning period on clear days without rain. Figure 4 illustrates the distribution of the most frequent sighting times, showing a significant concentration of reports during the morning, particularly

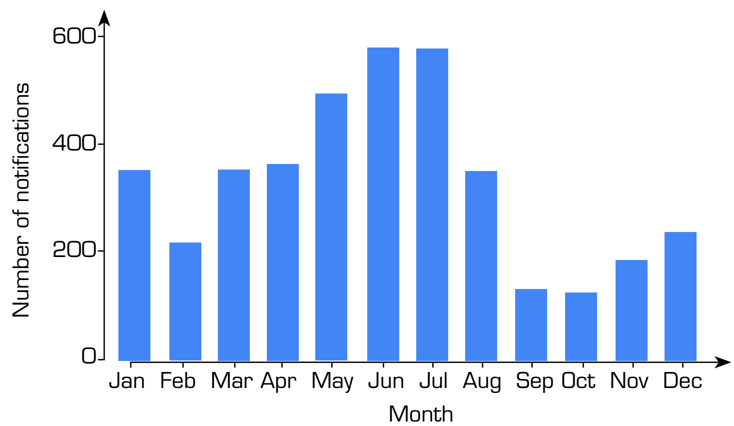


Source: Elaborated by the authors.

Figure 4. Main time periods of balloon sighting reports.

between 06:00 h and 12:00 h, suggesting that fireworks balloons are more frequently observed during daylight hours, with a notable peak around noon and scattered occurrences throughout the day. During the early morning hours (mainly at midnight), sightings are less frequent but still present. During the study period, more than 700 incidents were recorded within the first minutes of the day. Certain moments show an unusually high number of reports, possibly indicating large-scale balloon release events.

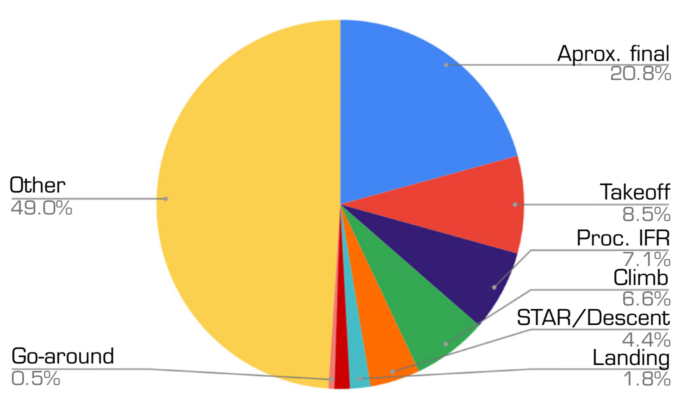
Regarding the distribution of reports throughout the year, the highest volume occurs during the *festas juninas* celebrations, as shown in Fig. 5. The months from May to August account for 46.39% of the total reports. Additionally, a significant number of reports are recorded during school holiday periods (December and January).



Source: Elaborated by the authors.

Figure 5. Balloon sighting reports by month of the year.

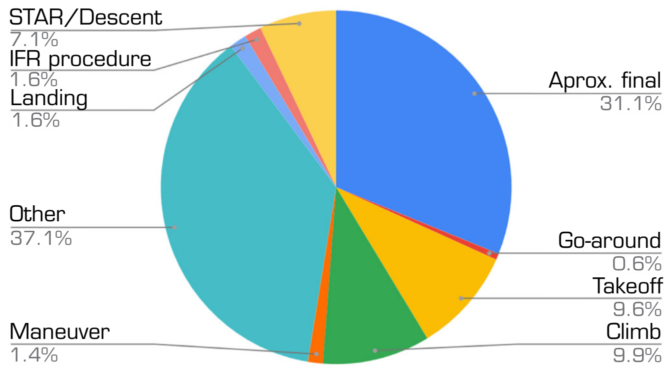
When analyzing the flight phase, it is observed that most sightings occurred during critical operational phases, either during landing or takeoff. As shown in Fig. 6, the total number of reports during the final approach, Instrument Flight Rules (IFR) procedures, descent/Standard Terminal Arrival Route (STAR), and landing accounts for nearly 36% of all notifications.



Source: Elaborated by the authors.

Figure 6. Percentage of balloon sightings by flight phase in Brazil.

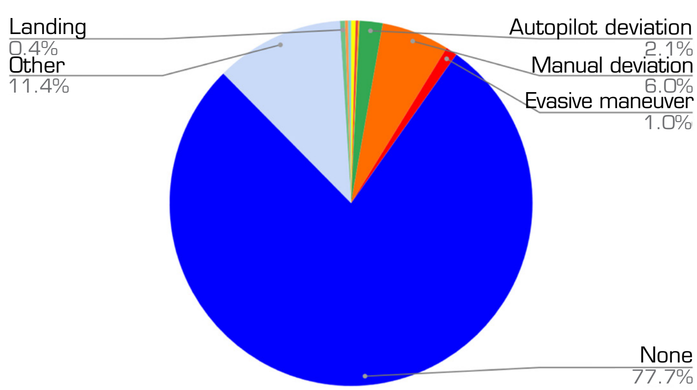
Additionally, takeoff and climb phases represent more than 16% of reports nationwide. Figure 7 presents data specifically for the state of São Paulo, which follows the same trend as Fig. 6. In São Paulo, the total number of reports involving descent operations exceeds 40%, while climb operations account for nearly 20% of all reports.



Source: Elaborated by the authors.

Figure 7. Percentage of balloon sightings by flight phase in the state of São Paulo.

According to the CENIPA database (2014–2023), approximately 6,902 actions were recorded to manage any type of accident or incident involving unmanned hot-air balloons during sightings in Brazil. Figure 8 shows that most reports do not indicate any interference; however, there are cases where adverse effects on flights occur, such as the need for manual deviations, autopilot deviations, and go-arounds.



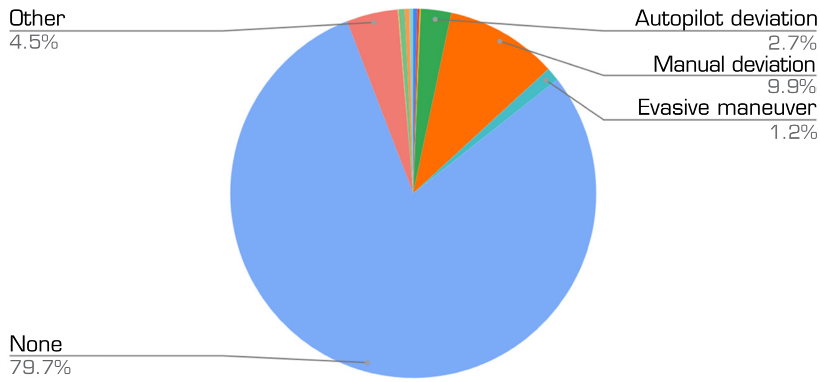
Source: Elaborated by the authors.

Figure 8. Percentage of occurrences by flight phase in Brazil.

Based on the same data collection period, in the state of São Paulo alone, 3,672 pilot actions were recorded to manage the approach of unmanned hot-air balloons during flight operations. Figure 9 highlights the same analysis for the state of São Paulo, where manual deviations and evasive maneuvers account for more than 10.5% of total occurrences.

The data indicate that a significant portion of balloon sightings occurs during critical flight phases, particularly approach, descent, and takeoff. However, most incidents do not escalate into accidents, which can be attributed to pilots' ability to execute evasive maneuvers and the ATC system's capacity to manage real-time risk mitigation. According to Figs. 8 and 9, approximately 10.5% of reports involved evasive actions, including manual deviations, autopilot disengagement, and go-arounds. These maneuvers play a crucial role in reducing the probability of collisions by preventing direct impacts with aircraft.

The significant discrepancy between the high number of balloon sightings and the relatively low incidence of formally reported accidents can be explained by various technical and operational factors. Firstly, underreporting is a critical issue in this context.



Source: Elaborated by the authors.

Figure 9. Percentage of occurrences by flight phase in the state of São Paulo.

Consequently, there is a high probability that minor incidents remain underreported or entirely unreported, especially when they do not cause noticeable alterations in aircraft operational performance.

Additionally, the low incidence of formally reported accidents is directly related to the effectiveness of evasive measures adopted by flight crews and ATC systems. Pilots frequently execute manual deviations, disengage autopilot systems, or perform go-around maneuvers upon sighting balloons near critical operational areas, such as final approach, landing, and takeoff phases. These actions have demonstrated a high success rate in preventing direct collisions, significantly reducing the likelihood of severe accidents. Furthermore, ATC significantly contributes through prompt interventions, such as issuing traffic alerts and even temporarily closing runways when an imminent risk is identified, as observed in specific events at Brazilian airports such as SBKP and SBRJ.

Therefore, the combination of these two primary factors – underreporting and the high effectiveness of evasive measures employed by aviation operators – explains the observed discrepancy between the total number of sightings and the relatively low number of formally recorded accidents.

ANALYSIS OF THE INDIVIDUAL SAFETY INDEX

By relating the number of flights per operational hour to the number of reports involving fireworks balloons, Eq. 1 (I) is applied. This index is calculated by multiplying by 100,000 the ratio between the number of events and the number of takeoffs. Table 6 highlights the year 2022 as the most critical, with 148.59 reports per 100,000 takeoffs in the country.

Although the 0.9157 correlation between notifications and collisions suggests that an increase in reports is directly associated with a higher risk of impact, the lack of detailed records on balloon-related aircraft damage may indicate underreporting of minor collisions.

One factor contributing to this underreporting is the absence of physical evidence. Unlike bird strikes, which often leave impact marks and biological residues on aircraft, balloons can disintegrate upon collision, making it more challenging to confirm

Table 6. National index (índice *nacional* [IN]) for unmanned balloon sightings (2014–2023).

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2014–2023
IN × 10^{5}	29.72	28.93	50.32	76.91	95.45	99.29	128.63	148.59	109.50	91.73	78.97

Source: Elaborated by the authors.

the cause of structural damage. As a result, minor damage to the fuselage, antennas, and sensors may go unnoticed until post-flight inspections.

Furthermore, the psychological and operational implications of reporting an incident may lead flight crews to avoid documenting minor impacts, particularly when no immediate operational consequences are observed. This hypothesis is supported by CENIPA data, which reveal a significantly higher volume of sighting reports compared to confirmed collisions. These findings underscore the need for enhanced post-flight inspections and more rigorous reporting protocols to ensure a comprehensive assessment of the risks associated with fireworks balloons.

RISK ANALYSIS

Based on the frequency, calculated as the number of cases divided by the total number of observations, the frequency of balloon sightings per number of flights in the country from 2014 to 2023 was $7.89 * 10^{-4}$, meaning approximately eight reports for every 10,000 flights.

The frequency of balloon sighting reports was analyzed for the most critical airports regarding notifications during their respective operations. It is important to note that flight statistics for embarkation and disembarkation were collected per airport through the HORUS platform, with the last update on July 24, 2024 (ANAC 2024). Notably, a significant number of fireworks balloon reports were recorded at SBJR, located in Rio de Janeiro, which had only 4,570 flights during the study period.

Table 7 presents the analysis of balloon sighting frequency relative to the number of flights at eight of Brazil's main airports from 2014 to 2023.

Table 7. Frequency for airports with most notifications.

ICAO	Number of notifications (2014–2023)	Number of flights (2014–2023)	Estimated flights/day	Estimated flights in notification area	Frequency
SBSP	475	1,487,184	407.45	193,538	2.45E-03
SBKP	825	1,098,487	300.96	248,288	3.32E-03
SBGR	1,353	2,431,739	666.23	901,409	1.50E-03
SBMT	139	623,713	171.00	23,752	5.85E-03
SBJR	353	4,570	1.25	442	7.99E-01
SBCT	222	539,181	147.72	32,794	6.77E-03
SBRJ	995	865,171	237.03	235,848	4.22E-03
SBGL	533	836,188	229.09	122,106	4.37E-03

Source: Elaborated by the authors.

Guarulhos (SBGR) leads in the absolute number of notifications (1,353), followed by SBRJ and SBKP. However, when considering relative frequency, which reflects the ratio between notifications and the number of flights in the notification areas, SBJR presents the highest frequency (7.99E-01), despite having a smaller absolute number of flights. Campo de Marte (SBMT) and Curitiba (SBCT) also have relatively high frequencies. These results suggest that, while major hubs have a high absolute number of notifications, smaller airports may face a proportionally higher risk of balloon collisions, requiring specific attention for risk mitigation.

Table 8 presents the probability, severity, and collision risk analysis involving balloons at six Brazilian airports from 2014 to 2023. The risks were calculated according to the FAA guidelines. For severity, category four was considered in most cases due to the presence of flight effects such as go-arounds, emergency landings, evasive maneuvers, and small fires within the airport grounds, among others reported by official notifications at the airports presented by CENIPA for the period from 2014 to 2023. Although SBBU reported a collision, it was excluded due to a lack of data.

Guarulhos (SBGR) stands out with the highest number of accidents (13), resulting in a collision probability of 1.44E-05 and a risk classification of "2B." Due to its moderate severity and high frequency, SBGR requires priority attention. Galeão (SBGL) and SBCT also present elevated risks (“2C” and “3C,” respectively) due to the combination of high collision probability and significant severity.

Viracopos (SBKP) and SBSP show lower risk, classified as “3D” and “2D,” respectively, indicating that, while the probability of collision is relatively low, continuous monitoring is still necessary. Campo de Marte (SBMT), evaluated based on the risk matrix for general aviation and small aircraft, presents a “5D” risk, highlighting the presence of balloons near operations with smaller aircraft but with a low risk of collisions.

Table 8, which correlates collision probability, impact severity, and operational risk, indicates that airports such as SBGR, SBGL, and SBCT exhibit elevated risk levels due to high sighting frequency combined with intense air traffic density. Conversely, smaller airports, such as SBMT and SBJR, report a lower absolute number of collisions, but their risk remains proportionally high due to the lower volume of flights. These findings emphasize the importance of targeted risk mitigation measures, particularly at high-risk locations, where balloon-related incidents could significantly disrupt air operations and compromise flight safety.

Table 8. Probability, severity, and risk at affected Brazilian airports.

ICAO	Accidents (2014–2023)	Estimated number of flights in the notification area	Probability of collision	Classification	Severity	Risk
SBSP	2	193,538	1,03E-05	D	2	2D
SBKP	2	248,288	8,06E-06	D	3	3D
SBGR	13	901,409	1,44E-05	B	2	2B
SBMT	1	23,752	4,21E-05	D	5	5D
SBCT	3	32,794	9,15E-05	C	3	3C
SBGL	4	122,106	3,28E-05	C	2	2C

Source: Elaborated by the authors.

The impact analysis of balloons in airspace must consider their physical properties, including weight, density, and construction materials. According to CENIPA (2013), small balloons tend to have low density and impact resistance, which reduces the likelihood of severe damage to aircraft. However, large balloons – often equipped with metal structures and explosive payloads – pose significantly greater risks. This was evidenced by the incident involving an Airbus A319, which collided with an advertising banner carried by a balloon, leading to damage to its airspeed sensors (pitot tube) and TAT sensor, compromising the aircraft’s flight instrumentation.

These results indicate that, despite differences in risk classifications, all airports require appropriate mitigation measures to reduce the likelihood of collisions, especially in locations where the combination of severity and probability places the risk at critical or moderately high levels.

The Pearson correlation analysis was performed to validate the linear relationship between balloon sightings and collision occurrences, resulting in a coefficient of 0.9157, indicating a strong positive correlation. This suggests that states with more reports tend to record more collisions, although the correlation does not imply direct causality. Other factors, such as air traffic density, may also influence the results, emphasizing the importance of preventive measures in areas with high incidence.

ECONOMIC IMPACTS, REGULATORY CHALLENGES, AND TECHNICAL SOLUTIONS

This assessment highlights the complex challenges posed by fireworks balloon incidents to Brazilian aviation authorities and air transportation systems. The high impact levels assigned to collision risk and fire hazards underscore the serious safety implications of these incidents. However, the lack of specific mitigation measures for most challenges and the unknown impact levels for several factors indicate significant gaps in our understanding and management of this issue.

Beyond the direct safety concerns, the economic impacts of fireworks balloon incidents on aviation operations require further investigation. These events can lead to flight delays, reroutings, emergency landings, and potential damage to aircraft, all of which impose significant costs on airlines and airport operators. Flight disruptions affect scheduling efficiency, increase fuel consumption, and may lead to passenger compensation claims, impacting the financial performance of air carriers. Additionally, aircraft damage, even if minor, can result in maintenance costs and operational downtime, further exacerbating economic losses.

The criminalization of balloon creators represents the primary regulatory response identified in the literature. While this measure has been implemented, its effectiveness remains unclear, and the associated enforcement costs have not been quantified. This suggests a need for further evaluation of regulatory strategies and their economic implications, particularly in terms of law enforcement expenditures and the financial burden on the judicial system.

The potentially significant operational costs for airlines, as implied by de Andrade *et al.* (2022), underscore the economic dimension of this issue. Although the authors do not present a detailed economic analysis, their discussion of systemic vulnerabilities exposed by past aviation incidents suggests the potential for considerable operational and financial repercussions. However, the lack of specific data on these costs – particularly in the context of fireworks balloon incidents – reveals a need for more targeted economic research. A comprehensive cost-benefit analysis of preventive measures, including enhanced surveillance and regulatory enforcement, could help justify investments in risk mitigation strategies.

Overall, this assessment reveals a complex interplay between safety concerns, economic impacts, and regulatory challenges in addressing fireworks balloon incidents in Brazilian aviation. The gaps in our current understanding suggest that this issue requires further attention from both researchers and policymakers to develop comprehensive and effective management strategies that account for both operational safety and economic sustainability.

Mitigating the risks posed by fireworks balloons in airspace requires the implementation of advanced technical solutions, encompassing monitoring and automatic detection, interception, regulation, and predictive models. The use of low-altitude radars and infrared sensors can detect balloon trajectories in real time, enabling early warnings for air traffic authorities. Additionally, computer vision and artificial intelligence systems can be trained to identify and track balloons through high-resolution cameras and thermal sensors, allowing for continuous monitoring (Hegyi and Jósvai 2019). Furthermore, autonomous drones equipped with infrared sensors can patrol critical areas, ensuring rapid responses to potential threats.

Integrating balloons into airspace management systems represents another effective approach. Studies highlight the feasibility of incorporating unmanned balloons into air traffic through predictive algorithms based on historical sighting data (Hegyi and Jósvai 2019). These models can forecast high-risk times and locations, enabling evasive strategies for aircraft and enhanced surveillance in vulnerable areas. Regarding interception, the use of interceptor drones equipped with capture nets may serve as a viable alternative to remove balloons before they reach critical altitudes. Moreover, research has explored the use of directed microwave weapons to disable the ignition mechanisms of fireworks carried by balloons (Lin 2016).

Another line of action involves ground-based mitigation systems, such as observation towers equipped with lasers, which could track and, if necessary, induce controlled combustion of balloon structures before they reach critical airspace. International tests also suggest the feasibility of using compressed air cannons to prevent balloons from ascending beyond safe altitudes (Zhang *et al.* 2017). In the regulatory domain, updating ICA 100-12 could be essential to reinforce sanctions against illegal balloon launches, integrating intelligent camera monitoring and automated fine enforcement for those responsible (Cruz 2021).

Beyond technological and regulatory solutions, preventive and educational strategies can help reduce this problem. Awareness campaigns on the fire and collision risks of fireworks balloons can be implemented in schools and communities, encouraging safer cultural alternatives, such as LED-equipped balloons instead of fireworks balloons (Thakur *et al.* 2010). The application of computational models and predictive analyses also proves to be a promising tool, as demonstrated by Indumathi *et al.* (2021), who used decision trees to predict occupational risks in the fireworks industry. This approach can be applied to aviation safety, utilizing CENIPA data to map risk patterns and optimize surveillance efforts.

Thus, the combination of detection, neutralization, regulation, and predictive modeling technologies can minimize the risks associated with fireworks balloons in Brazilian airspace, ensuring greater aviation safety and reducing the incidence of such incidents.

CONCLUSION

This study analyzed the risks posed by fireworks balloons and their impact on the operational safety of Brazilian airports. Using data on sightings and collision reports from 2014 to 2023, the research identified a high concentration of occurrences in the states of São Paulo, Rio de Janeiro, and Paraná, with SBGR, SBRJ, and SBJR airports being among the most affected. The uncontrollability of balloons and their presence in critical airspace areas, particularly during approach, descent, and takeoff phases, significantly increase the risk of collisions.

Despite the high number of notifications at major hubs, smaller airports, such as SBJR, face a proportionally higher risk of balloon-related incidents due to their lower traffic volume and lack of structured mitigation strategies. The statistical correlation (0.9157) between balloon sightings and confirmed collisions reinforces the need for more effective preventive measures. However, the relatively low number of recorded accidents, despite frequent sightings, can be attributed to three interrelated factors: (i) successful evasive actions by pilots and ATC, preventing direct impacts; (ii) underreporting of minor collisions, particularly those with no immediate operational consequences; (iii) the structural characteristics of balloons, which may disintegrate upon impact, making damage assessment challenging.

Given these findings, enhancing detection technologies is imperative. The implementation of low-altitude radar systems, artificial intelligence-based tracking, and automated monitoring of balloon trajectories would significantly improve risk assessment and enable proactive threat mitigation. Additionally, standardizing incident reports and integrating them into aviation safety databases would contribute to a more comprehensive understanding of balloon-related hazards.

To effectively mitigate these risks, a multifaceted approach is required. Stricter regulatory enforcement, coupled with advanced surveillance technologies and operational countermeasures, such as interceptor drones and real-time airspace monitoring, could substantially reduce the likelihood of balloon incursions. Moreover, collaboration between aviation authorities, airport operators, law enforcement agencies, and the broader community is essential to ensuring Brazilian airspace safety.

Lastly, the 2016 downgrade of Brazilian airspace safety by IFALPA, as well as the growing complexity of airspace management with the introduction of new aerial technologies such as drones and eVTOLs, underscore the urgent need for comprehensive risk management strategies. Future research should focus on refining predictive models, evaluating economic impacts, and assessing the effectiveness of regulatory measures to ensure that fireworks balloon incidents do not compromise aviation safety.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Bandeira MCGSP and Castro AMA; **Methodology:** Castro AMA and Bandeira MCGSP; **Software:** Castro AMA; **Validation:** Castro AMA, Bandeira MCGSP and Correia AR; **Formal analysis:** Castro AMA, Bandeira MCGSP, and Correia AR; **Investigation:** Castro AMA; **Resources:** Bandeira MCGSP; **Data Curation:** Castro AMA; **Writing – Original Draft:** Castro AMA and Bandeira MCGSP; **Writing – Review & Editing:** Bandeira MCGSP and Correia AR; **Visualization:** Castro AMA; **Supervision:** Bandeira MCGSP and Correia AR; **Project administration:** Bandeira MCGSP; **Funding acquisition:** Bandeira MCGSP and Correia AR; **Final approval:** Bandeira MCGSP.

DATA AVAILABILITY STATEMENT

The data will be available upon request.

FUNDING

Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)
Grant No: 407352/2022-8 and 408320/2022-2

ACKNOWLEDGEMENTS

The authors acknowledges the financial support provided by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under the Programa de Iniciação Tecnológica (ITC-A), granted through CNPq/Ministério da Ciência, Tecnologia e Inovações (MCTI)/Secretaria de Empreendedorismo e Inovação (SEMPI): 408320/2022-2 process, for the development of this study.

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