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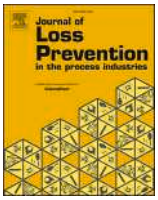

Coloured powder potential dust explosions

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ABSTRACT

The use of Coloured powder (Holi powder orcolour dust) has been largely used in India for their festivities. Due to their popularity is extensive around the world since the popularity of the parties and events with this kind of show is increasing considerably. Despite the fact of its extensive use, its highly flammable nature is poorly known. Currently, some serious accidents related to the Coloured powder have been registered. Coloured powder organic nature implies a significant increase in the probability to form an explosive atmosphere as their use includes dust dispersion, leading to explosion hazards as has been previously reported. Moreover, it is important to take into account the effects on the flammability of the additives and the colorings existing in the Coloured powder as they might increase the hazard. To properly understand Coloured powder potential for producing an explosive atmosphere, and the attached risk of dust explosions, several samples were tested. Coloured powder from 6 different manufacturers were gathered. Each manufacturer provided several colours (between 5 and 8) which were characterized through moisture content and particle size determination. Once each sample was characterized, screening tests were performed on each sample determining whether ignition was produced or not. Those screening tests were carried out under certain conditions using the equipment for minimum ignition temperature on cloud determination (0.5 g set at 500 °C and 0.5 bar), and minimum ignition energy determination (using 100 and 300 mJ energies and 900 and 1200 mg). From those test results, important differences were seen between manufacturers, but most important, differences between colours of the same manufacturer were observed. The screening tests allowed the selection of 11 samples that were fully characterized through thermogravimetric analysis, maximum pressure of explosion, K_{st}, minimum ignition temperature on cloud, and minimum ignition energy. When carrying out thermogravimetric analysis, some samples increased mass at temperatures close to 300 °C and unexpectedly absorbed energy, followed by the expected combustion reaction at higher temperatures. From the obtained results it was noticed that the colour powders that included talcum in its composition did not produce explosion. Flammability and explosion tests, again, showed important differences between manufacturers and colours, and so it was possible to determine the relative flash fire and explosion risks of the various tested powders.

1. Introduction

Dust explosions have been studied for decades due to the high explosion hazard associated with the use, storage and transport of finely divided solids (Eckhoff, 2003a, 2003b, 2009; Fernandez-Anez et al., 2020). Because of that fact, a proper evaluation of new combustible particulate materials being used in industrial facilities should include characterizing their potential for ignitions and associated flash fires and explosions. Dust explosions are produced when five factors take place simultaneously: combustible dust, presence of oxygen, confinement, dispersion, and ignition source. Indeed, if combustible dust is dispersed into the air in a confined space an explosive atmosphere is generated and, if an ignition source is applied to the explosive atmosphere with enough energy, it will lead to a dust explosion (Amyotte, 2014; Eckhoff, 2005).

Besides those factors, dust explosion risk depends on dust material (physical and chemical properties) and thus, on its chemical composition, moisture, particle size, compaction, etc., (Zhang et al., 2018). Hence, these parameters present an effect on the flammability properties of dusts (Amyotte et al., 2007; Castro et al., 2013; Hassan et al., 2014).

Due to the wide variety of combustible dust, their associated problems take place in several sectors such as the manufacturing, food

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processing industry, pharmaceutical products, power generation industry (solid fuels), etc., as the processes that occur in those industries can produce small particles that might lead to explosive atmospheres. Even more, the risk increases when accumulation and dispersion are not controlled (Medic et al., 2014; Wu et al., 2019). Indeed, nowadays industrial accidents related to dust explosions are still a crucial issue for companies due to their consequence severity: dust explosions produce important human, economic and environmental losses (Taveau, 2017). Because of that, a decrease in industrial accidents in the last years took place. However, dust accidents still happen (Abbasi and Abbasi, 2007; Dobashi, 2017) as new materials (such as biofuels, chemical products, etc.) are used every day without having a deep knowledge of their ignition behaviour (Krigstin et al., 2018).

Dust explosions are not limited to process industries or mines, but also to other scenarios that may affect civil safety. Some daily products such as organic food or medicines can generate explosive dust clouds, but their regular use does not imply a risk for citizens. Nevertheless, in the last years coloured powder (Holi powder) has become popular, due to the expansion around the world of one of the most popular festivals in India, the Holi party. This type of powder can involve a serious risk that must be addressed, as its use typically consists of generating a dust cloud by means of suspended coloured (or Holi) powder. These festivals started in India as a cultural celebration, but nowadays, their colourful attractive effects have involved a big increase in their use throughout the world. Such festivals originally were celebrated outdoors, nevertheless, nowadays these events take place also indoors. When the coloured powder material is susceptible to ignition, these confined conditions pose a higher probability to produce an explosion (Taveau, 2017). However, even in the absence of confinement, a flash fire could pose an important hazard.

The most typical composition of coloured powder is based on organic matter, being manufactured from organic substances such as corn starch or rice starch, although they can also be composed of inorganic substances such as talcum ((FOPH), 2017). In order to obtain a colour powder, synthetic pigments and chemical dyes are added. There are some research works regarding the effect of coloured powder on health or air quality (Bossmann et al., 2016; Gupta et al., 2018, 2019; Liao et al., 2016; Velpandian et al., 2007) as its use might be harmful and toxic; however, their flammability properties were poorly studied, and a lack of safety measures has led to accidents during those events (Kukfisz and Piec, 2021). These products are readily available in physical and online shops, without any reference to the risk of explosion. In fact, one of the manufacturers studied in this research indicates on a label that it is a non-flammable product. For this reason, it is essential to carry out an extensive investigation into the flammability characteristics of this product, in order to determine its safe conditions of use. Considering that the coloured powder main raw matter have been largely studied (mainly as biomass) due to their flammability (Addai et al., 2015; Han et al., 2020; Jiang et al., 2014; Zhang et al., 2017) and the industrial accidents produced by their use are well known (Chen et al., 2017; Han et al., 2020; Randeberg and Eckhoff, 2006; Zhang et al., 2017), it is important to evaluate the flammability of the coloured powder in order to prevent further accidents.

Some of the parameters that influence dust flammability and ignition, such as particle size, moisture, ash content or flammable additives vary depending on the manufacturer (Amez Arenillas et al., 2019), which means that the flammable nature of the powder may, therefore, change considerably from one manufacturer to another. The coloured powder organic nature gives a hint regarding its flammable behaviour, however, not every coloured powder is composed by organic matter, and the additives and dyes directly affect the flammability of this kind of dust.

Indeed, Kukfisz et al. carried out a study comparing flammability and explosion severity parameters for three different coloured powders (Kukfisz and Piec, 2021). It was found that minimum ignition energy values were lower than 300 mJ and minimum ignition temperatures were between 430 and 450 °C; characteristics that showed the flammable nature of this kind of dust. Furthermore, they also carry out explosion severity tests finding out that corn-starch based coloured powders meet the requirements to be considered not only flammable but explosive dusts.

In order to characterize coloured powder according to its flammable nature, the present research work departs from a previous study (Amez Arenillas et al., 2019) where a preliminary assessment was carried out and differences between manufacturers and colours were found. The study proved the existence of high flammability properties on this kind of dust developing a risk analysis for different samples from six different manufacturers. In the present research, the authors intend to determine further ignition and explosion severity characteristics in order to provide the needed knowledge to fulfil the safety measures required to assure public safety when handling coloured powder.

To reach this purpose samples from 6 different manufacturers and different colours were collected. Each sample was characterized through particle size distribution and moisture content. Afterwards, ignition screening tests were performed to find differences between manufacturers and colours. Furthermore, from the screening tests results, 11 samples were selected to perform ignition and severity explosion characterization tests. Through this characterization, ignition sensitivity was assessed, and safety recommendations and prevention measures can be concluded.

2. Experiments

The selected coloured powders for the present study were commercially available. Most of those manufacturers did not provide enough information regarding coloured powders composition. As previously pointed out, some of them even labelled coloured powder packages as “non-flammable” (manufacturer 2). A total of 6 manufacturers were selected from which different colours were collected. Table 1 shows each manufacturer’s studied colours, together with composition and safety recommendations. Regarding its origin, only manufacturers 3 and 4 provide information (made in India).

Each sample was characterized through particle size distribution and moisture content. Particle size distribution was determined using Malvern Mastersizer 2000 instrument that provides results using laser diffraction technique and Fraunhofer approximation (assumes that the particle is much larger than the light wavelength). From this technique d10, d50 and d90 parameters were obtained.

Moisture content was determined using a Mettler Toledo HB43–S halogen moisture analyser. A disposable pan is tared and filled with 1 ± 0.1 g of sample as a uniform layer and placed inside the analyser. For each sample, moisture content was determined 3 times and the average result was reported.

2.1. Screening tests

The screening tests were carried out using the equipment for Minimum Ignition Energy (MIE) and Minimum Ignition Temperature on cloud (MITc) determination. Screening tests were carried out in order to find significant differences between colours and manufacturers applying economic and fast tests. Because of that, not complete standardized procedure was carried out, but pre-defined conditions were used. In particular, for minimum ignition temperature on cloud determination, 0.5 g of sample were set at 500 °C and using 0.5 bar pressure for dust dispersion. These conditions are established according to the probability of ignition of the dust and the experience observed in the laboratory. The result of the test is defined as positive if the ignition was produced at those fixed conditions, and negative, if no ignition was observed.

Also, a simplified procedure was used for MIE determination, using a Kuhner Mike-3 equipment; however, two sample concentrations were used. The first test was carried out placing 900 mg of sample and applying 100 mJ sparks, the second one was set at 900 mg but increasing

Table 1
Selected colours and manufacturers.

	Red	Orange	Yellow	Purple	Blue	Pink	Green	Dark blue	Composition	Safety recommendations
Manufacturer 1		X		X	X				Corn-starch, talcum and FD&C Approved Dyes	To use in open air or ventilated spaces
Manufacturer 2	X	X			X	X	X		Corn-starch and food colouring	To use in open air. Not intended for use in small, confined, poorly ventilated spaces
Manufacturer 3	X	X	X		X	X	X		Corn-starch and food colouring	Do not use indoors
Manufacturer 4	X	X	X	X	X	X	X	X	Corn-starch (99%) and safe dyes (1%)	To use in open air or ventilated spaces
Manufacturer 5	X	X	X	X	X	X	X	X	Corn-starch (99%) and food colouring (1%)	Do not use in enclosed or poorly ventilated areas
Manufacturer 6		X	X	X	X	X	X		Corn-starch, bicarbonate, sodium chloride and food dyes	For use in outdoor or well-ventilated areas

the energy up to 300 mJ. The third test was carried out using 1200 mg of sample and applying 300 mJ. In each test, an ignition delay of 120 ms was applied. Again, the result of the test is considered positive if the ignition was produced at those fixed conditions, and negative, if no ignition was observed.

Screening tests results allowed the selection of the samples that underwent the ignition sensitivity and explosion severity test. For each manufacturer, two samples were selected except for manufacturer 1, whose screening test provides preliminary non-flammable results for all samples, so only one colour was selected due to the predictable similarity between the results of the ignition sensitivity and explosion severity test.

2.2. Ignition sensitivity

Materials ignition sensitivity is typically defined through four tests: lower explosion limit (LEL), minimum ignition temperature on layer (MITl), minimum ignition temperature on cloud (MITc) and minimum ignition energy (MIE); the first one defined by the standard EN 14034–3:2006 and the others by the standard ISO/IEC 80079-20-2:2016 (European committee for standardization CEN-CENELEC, 2016). However, MITl was not carried out as this study focuses on dust explosions in which dust clouds need to be produced, which only takes place in MIE and MITc. Neither was LEL as explosion severity provides more detailed information.

For MIE, the standard defines the required procedure to determine minimum ignition energy of the sample, which is the minimum energy required to ignite a cloud produced by sample suspension in the air. The test was carried out using a Mike 3 apparatus, which is based on a Hartmann Tube equipment. The apparatus consists of a vertical cylindrical glass tube provided with two opposing ignition electrodes separated 6 mm between each other. The tube is connected to a 50 mL air reservoir pressurized that disperses the sample and produces the cloud inside the tube. Different concentrations were tested, applying a single ignition delay of 120 ms and spark energies of 1, 3, 10, 30, 100, 300 and 1000 mJ. The software calculates minimum ignition energy by applying the following equation:

$$\log(\mathrm{MIE}) = \log(\mathrm{E_2}) - \mathrm{I_{E_2}} \cdot \frac{\log(\mathrm{E_2}) - \log(\mathrm{E_1})}{(\mathrm{NI} + \mathrm{I})_{\mathrm{E_2}} + 1}$$

Where.

- *MIE* is the minimum ignition energy expressed in millijoules, mJ.
- E_2 is the energy at which the ignition is produced expressed in millijoules, mJ.
- I_{E2} is the number of tests at which the ignition is produced at E_2 energy.
- $(NI + I)_{E2}$ is the total number of tests carried out at E_2 energy.
- E_1 is the highest energy at which no ignition takes place expressed in millijoules, mJ.

On the other hand, MITc is determined using a vertical furnace, based on the Godbert-Greenwald Apparatus (Eckhoff, 2019) whose temperature can be controlled. A silicon tube is placed vertically in the furnace with its bottom open to the air. The top is connected to a glass adapter where the sample is placed, which is connected to a valve that releases compressed air to disperse the dust and produce the dust cloud inside the furnace. For the test, 0.3 g of sample are placed on the glass tube and the furnace temperature is set at 500 °C. If ignition is not produced, the test is repeated increasing temperature 50 K until ignition takes place or up to 900 °C, which was the maximum temperature the equipment could reach. After ignition is produced, mass and dispersion pressure are varied until the most vigorous ignition is produced. Afterwards, using the same mass and dispersion pressure, further tests are carried out reducing temperature in steps of 20 K, or 10 K below 300 °C, until no ignition is obtained after 10 attempts.

2.3. Explosion severity

Explosion severity parameters are defined using 20-L sphere equipment, in which dust is dispersed by means of a pressurized dust container (which generates a dispersion overpressure of 20 bar) through a quick-acting valve and a dispersion nozzle, to form a dust cloud under standard conditions of pressure and temperature and applying ignition using two 5000 J igniters, located in the centre of the sphere. Again, the procedure is standardized through EN 14034–2:2006 + A1:2011.

The apparatus is equipped with pressure sensors that record explosion pressure in time, so maximum explosion pressure (P_{max}) and pressure-time rate (dP/dt) are defined. The definition of P_{max} provides important information regarding flash fire severity, as is a surrogate for the flame temperature which is the main parameter for flash fire severity characterization. Different concentrations were tested, applying an ignition delay of 60 ms to determine the maximum rate of explosion pressure rise $(dP/dt)_{max}$ and the maximum explosion pressure P_{max}. The $(dP/dt)_{max}$ allows the determination of the standard or characteristic constant (K_{st} or K_{max}) as:

$$\mathrm{K_{st}} = (\mathrm{dP/dt})_{\mathrm{max}} \cdot \sqrt[V]{}$$

where V represents the volume of the sphere expressed in m^3.

Table 2
Rating explosion severity according to K_{st}.

Dust Explosion Class	K_{st} (bar · m/s)	Characteristic
St 0	0	No explosion
St 1	(0, 200]	Weak explosion
St 2	(200, 300]	Strong explosion
St 3	>300	Very strong explosion

Furthermore, K_{st} provides information regarding explosion severity as shows Table 2.

2.4. Simultaneous thermal analysis (STA)

Simultaneous thermal analysis (STA) consists of performing TGA and DSC simultaneously. Thermogravimetric analysis (TGA) is an analytical technique that monitors sample weights changes while applying heat so thermal stability and volatile fractions can be determined. On the other hand, differential scanning calorimetry (DSC) is a thermal technique that measures the energy exchanged from a sample that undergoes a physical or chemical change. The technique measures the difference in the amount of heat required to increase the temperature of a sample and references it as a function of temperature. In other words, DSC analysis calculates the amount of energy required to increase sample's temperature by comparing it to a reference material.

Several authors have used simultaneous thermal analysis to address flammability parameters (Cao et al., 2017; Garcia-Torrent et al., 2015; Janković et al., 2020; Manić et al., 2021). The use of thermogravimetric analysis allows defining material's thermal behaviour which will provide information useful to assess the reaction that takes place. If combustion reaction is simulated, TGA allows defining at which temperature the reaction accelerates, together with the temperature at which the mass degradation rate reaches its maximum. Moreover, if STA is performed, the results from DSC curves can define the temperature at which the reaction changes from endothermic to exothermic, releasing heat that can increase self-ignition risk, together with the acceleration of the reaction.

In the present study, Mettler Toledo TG-DSC T50 apparatus was used, together with 70 μL alumina crucibles where 30 ± 2 mg of sample are placed. The test is carried out by controlling the atmosphere inside the furnace, the initial and final temperature (30 and 800 °C respectively), and the heating rate (β = 50 K/min), and records temperature, mass, heat flow and time during the whole procedure. The furnace atmosphere was air (simulated by using 79% nitrogen and 21% oxygen) with a 50 mL/min flow, so one of the key reactions was oxidation.

3. Results and discussion

3.1. Samples characterization

As mentioned above, each sample was characterized through particle size and moisture content. Table 3 shows the results obtained for each sample, together with the standard deviation for each parameter and manufacturer (calculated considering every colour).

Samples from manufacturer 6 show much higher d50 and d90 values, nevertheless, particle size does never exceed 500 μm which is the nominal size under which dust can produce explosive atmospheres. It is remarkable the colour effect in both particle size and moisture, as for the same manufacturer, samples heavily differ depending on colour. Those differences are clearly seen when assessing standard deviation (σ_i). When comparing manufacturer 1, 2, 3 and 6 colours, it can be noticed that high σ_i values are obtained for particle size determination, especially d90. On the other hand, moisture is a more homogeneous parameter besides samples 2 and 6, where differences between colours are clearly noticed. This fact means that for the same raw material composition, the applied dyes produce significant physical changes. For example, when considering manufacturer 2 moisture content, it is noticed that blue and pink colours present low moisture content, while the remaining colours show >10% moisture. On the other hand, manufacturers 3, 4 and 5 presented more homogeneous results. As physical parameters affect explosion severity and flammability parameters (Castells et al., 2020; Eckhoff and Mathisen, 1978; Pietraccini et al., 2021; Rifella et al., 2019; Russo et al., 2013; Zhang et al., 2017), it can be deduced that not every colour from the same manufacturer will behave identically in subsequent tests.

Table 3
Samples characterization.

Manufacturer	Colour	d10 (μm)	d50 (μm)	d90 (μm)	Moisture (%)
1	Orange	1.34	12.07	67.57	3.52
1	Purple	1.85	12.04	56.06	2.10
1	Blue	1.24	7.97	39.58	1.97
Standard Deviation (σ_1)		**0.33**	**2.36**	**14.07**	**0.87**
2	Red	9.33	14.39	22.03	10.25
2	Orange	8.93	13.69	20.75	10.34
2	Blue	2.76	10.16	25.81	1.91
2	Pink	2.20	8.48	32.34	0.67
2	Green	8.88	13.34	19.83	10.57
Standard Deviation (σ_2)		**3.61**	**2.56**	**5.11**	**5.00**
3	Red	8.52	14.26	24.2	9.90
3	Orange	8.60	14.50	26.92	10.20
3	Yellow	8.16	15.34	60.14	10.24
3	Blue	8.31	15.00	33.84	9.70
3	Pink	8.57	14.32	26.49	10.14
3	Green	8.50	15.52	37.84	9.78
Standard Deviation (σ_3)		**0.17**	**0.54**	**13.38**	**0.23**
4	Red	9.10	14.02	21.42	11.26
4	Orange	8.94	13.29	19.55	10.72
4	Yellow	9.38	13.98	20.69	10.60
4	Purple	9.43	14.05	20.78	10.64
4	Blue	9.66	13.70	19.32	10.44
4	Pink	9.46	14.06	20.78	10.66
4	Green	9.50	13.59	19.33	10.55
4	Dark Blue	9.32	13.91	20.60	10.18
Standard Deviation (σ_4)		**0.23**	**0.28**	**0.79**	**0.31**
5	Red	9.31	13.81	20.28	10.06
5	Orange	9.10	13.80	20.72	11.21
5	Yellow	9.16	14.04	21.39	13.65
5	Purple	9.53	13.62	19.35	12.79
5	Blue	9.54	13.61	19.29	12.02
5	Pink	9.11	13.56	20.00	11.52
5	Green	8.95	13.64	20.59	9.93
5	Dark Blue	9.28	13.89	20.61	10.25
Standard Deviation (σ_5)		**0.21**	**0.17**	**0.71**	**1.35**
6	Orange	10.41	79.58	335.67	5.24
6	Yellow	9.97	21.91	335.22	5.95
6	Purple	10.89	62.96	334.41	11.02
6	Blue	10.17	26.63	301.05	5.68
6	Pink	11.33	127.30	391.10	4.37
6	Green	10.41	110.53	328.11	10.46
Standard Deviation (σ_6)		**0.50**	**43.01**	**29.35**	**2.86**

Standard deviation was calculated in order to assess the effect of the colour in each manufacturer powder, in other words, it represents the influence of the dyes on particle size and moisture.

3.2. Screening tests

The screening tests results were considered positive if at last one ignition was detected, and negative if no ignition was observed. Fig. 1 plots the results for each sample, where the bars are coloured in the colour they represent.

From the screening test can be noticed that samples have a tend to produce more positive results when testing MITc than MIE, as no positive result was found in MIE if not found previously in MITc. Furthermore, from the results, it is shown that manufacturers 1 and 6 can be preliminary considered the least flammable products. This fact can be explained due to its composition. Manufacturer 1 raw material composition is not only corn-starch, but also talcum which is an inert material and reduces ignition sensitivity. On the other hand, coloured powder from manufacturer 6 is composed of corn-starch, bicarbonate, and sodium chloride, being these last two inert materials. However, for this manufacturer, the addition of inert material does not completely remove flammability risks as 5 of 6 samples resulted positive when testing MITc.

The screening tests allowed the selection of 11 samples for complete characterization. For each manufacturer, two samples were selected: one with a high ignition sensitivity, which achieved the ignition in all of the largest number of tests, and another with less sensitivity, which did not produce ignition in any or only in a small number of tests (besides

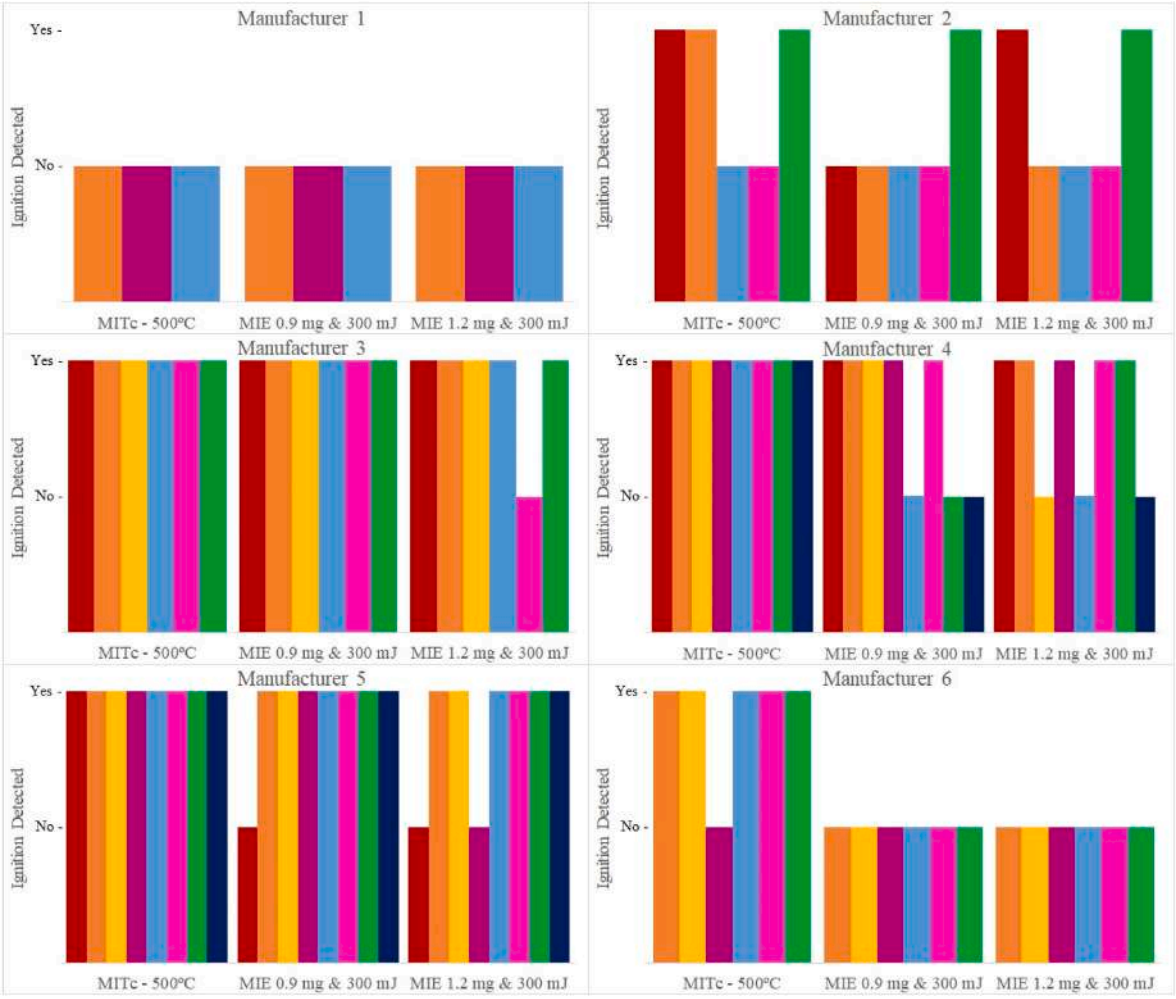

Fig. 1. Screening test results.

manufacturer 1, from which only one sample was selected). Those samples were characterized through proximate analysis, in order to have a better knowledge of their composition. Those results are shown in Table 4.

As ashes are the product of incomplete combustion, the high ash content for samples produced by manufacturers 1, 2 and 6 preliminary indicates that lower explosion severity will be obtained when testing those samples, especially manufacturer 1 whose ash content is the highest. Indeed, manufacturers 1 and 6 included inert materials which mean that their ash content should be higher, as inert materials are not affected by combustion reactions. When carrying out the ash test, some kind of explosion was detected when temperature reached around 300 °C, as an important amount of smoke was produced inside the furnace together with low explosion sounds, similar to small fireworks. When the furnace was open, it was noticed, as it is shown in Fig. 2, that some of the samples heavily increased their mass overflowing the crucible. However, this phenomenon will be addressed through TGA as it will detect the mass increase and the temperature at which is produced, together with heat flow transfer.

Table 4
Selected samples proximate analysis.

Manufacturer	Colour	Moisture (%)	Volatiles (%)	Ash (%)
1	Purple	2.10	29.84	66.82
2	Blue	1.91	61.16	31.43
2	Green	10.57	58.92	23.81
3	Yellow	10.24	84.97	0.25
3	Blue	9.70	86.42	0.14
4	Red	11.26	84.93	0.20
4	Blue	10.44	85.46	0.33
5	Red	10.06	91.24	1.38
5	Yellow	13.65	95.72	0.60
6	Yellow	5.95	47.18	26.73
6	Purple	11.02	43.62	26.65

3.3. Ignition sensitivity and explosion severity

The obtained results from MITc and 20-L sphere are shown in Table 5. It can be noticed that, according to K_{st} characterization, every sample classifies as "weak explosion" besides manufacturer 1, where no explosion was detected.

It might seem that complete test results are not consistent with screening test results, especially regarding MITc as some samples did not produce ignition when carrying out MITc screening test at 500 °C but when carrying out the complete procedure MITc below 500 °C was found. It can be explained since complete procedure not only modifies temperature but also sample weight and pressure, so that concentration and turbulence are thoroughly modified. Because of that, MITc could be lower than 500 °C. A similar situation takes place when considering manufacturer 4-blue sample, whose MIE is set at 190 mJ and it was found negative when testing MIE screening tests at 300 mJ. Again, the complete procedure modifies concentration and ignition delay, so the MIE can be lower than the energy applied when performing screening tests. Nevertheless, the use of screening tests allowed to select some samples that presented different behaviour so when carrying out the

Fig. 2. Ash content analysis.

Table 5
Flammable and explosion severity results.

Manufacturer	Colour	MIE (mJ)	MITc (°C)	P_{max} (bar)	$(dP/dt)_{max}$ (bar/s)	K_{st} (bar · m/s)
1	Purple	150	480	0	0	0
2	Blue	>1000	490	6.5	71	19
2	Green	55	420	7.5	218	59
3	Yellow	79	400	8.2	351	95
3	Blue	55	390	8.1	344	93
4	Red	380	400	8.5	373	101
4	Blue	190	380	8.4	354	96
5	Red	>1000	420	7.8	376	102
5	Yellow	240	400	8.8	518	141
6	Yellow	>1000	510	6.5	307	83
6	Purple	>1000	460	6.6	43	12

complete test procedure, those differences could be addressed. If the manufacturers coloured powders flammability and explosion severity parameters are considered by comparing screening and complete tests, the same tendencies can be found. Manufacturers 1, 2 and 6 showed less risk than manufacturers 3, 4 and 5, tendency which is according to the results plotted in Fig. 1.

Overall MITc results are consistent with results published by Kukfisz and Piec (2021), as temperature range varies between 400 and 500 °C. However, they found the lowest MITc value for the sample containing talcum, while in the present study talcum, as an inert material, makes ignition more difficult, leading to greater temperatures. Between colours of the same manufacturer, no significant differences of MITc were found, besides manufacturer 6, whose samples differ 50 K. However, the same cannot be said about MIE, as some manufacturers (1 and 5 mainly) show significantly low energies for one of their samples, and greater than 1000 mJ for the other one. Even if, according to packaging specifications, manufacturers 4 and 5 present the same composition, different behaviour was noticed between both, even considering the same colour.

As it has been mentioned, weak explosions were detected, as the maximum pressure rate rarely increases over 400 bar/s. However, significant pressures were detected, especially for manufacturers 3, 4 and 5, which also produced the greatest pressure rates and, therefore, K_{st}. As previously mentioned, this fact is related to samples ash content. Indeed, as it was suggested in the previous section, manufacturer 1 high ash content leads to no explosion detection when performing the test. If compared to the results obtained by Kukfisz and Piec (2021), samples 3, 4 and 5 behave similarly to their results for corn-starch. According to packaging specifications, samples 4 and 5 present a composition of 99% corn-starch, which explains the similar trends. For sample 3, no exact composition was provided by the manufacturer, however, the results clearly show that corn-starch is present in high concentrations. On the other hand, manufacturer 1, which included talcum in their samples, did not generate explosion while the talcum sample tested by Kukfisz and Piec (2021), did. It can be deduced that manufacturer 1 samples presented higher talcum concentrations which lead to no explosion.

Nevertheless, the obtained results show that most of the samples present a high content of corn-starch and, therefore, a true explosion and flash fire risk is implied when using coloured powder (Holi powder), particularly considering that its use involves dust dispersion in the air, and so, producing explosive atmospheres.

The obtained values were compared to previously published literature for corn-starch dust. Several authors have studied corn-starch flammability and explosion severity parameters (Addai et al., 2015; Bu et al., 2019; Chatrathi, 1994; Li et al., 2020), concluding that maximum explosion pressure locates between 8.3 and 9.4 bar, K_{st} index between 92 and 242, MIE around 40–88 mJ and MITc close to 450 °C. Of course, the values do not depend only on the chemical composition of the sample but also on its particle size (Eckhoff, 2003a, 2003b), so only literature whose samples had similar physical properties have been considered. Nevertheless, the literature values can be useful in order to assess the effect of dyes addition. The samples tested in this study do not fit those ranges. Only MITc showed similar and homogeneous values that meet literature in several samples. This fact means that the effect of dyes has to be addressed. Nevertheless, it can be noticed that, according to previously published literature, samples from manufacturer 2 and yellow sample from manufacturer 3, presented lower MIE values than some corn-starch samples. On the other hand, the obtained explosive parameters are, in most of the cases, lower than the previously published literature, however, it is important to highlight the high values obtained for manufacturer 5 samples and manufacturer blue sample. However, those parameters significantly depend on moisture content and particle size distribution, leading to a difficult comparison between the results reported by other authors and the samples tested in the present study.

Manufacturers 1 and 6 included inert materials in their composition, which leads to less explosion and flammable risks. As several studies pointed out (Wang et al., 2019), the addition of inert materials can significantly reduce dust explosions. Studies showed that, depending on the sample, some inert materials can work better than others. For example, Dai et al. (2020) concluded that bicarbonate produces less inertization than other materials such as sodium phosphates, however, Going and Snoeys (2002) found that bicarbonate showed a better explosion suppression effect than talcum.

On the other hand, manufacturers 2, 3, 4 and 5 compositions are corn-starch and colouring dyes. It is a logical assumption to suppose that every manufacturer uses the same corn-starch for each colour, which means that differences found between colours are due to the addition of dyes. For example, regarding explosion severity, the addition of yellow dyes to manufacturer 5 corn-starch produces a significant change in K_{st} index if compared to red dyes. Indeed, yellow dyes also produced higher

K_{st} values for manufacturers 6 and 3, although no big differences were appreciated.

Moreover, regarding ignition properties, significant changes were produced in different colours. For example, minimum ignition energy changed drastically when testing manufacturer 2 samples. However, minimum ignition temperature did not show such an important effect of dyes, although small differences were found. This fact indicates that dyes produce a different effect on ignition sensibility and explosion severity. Of course, particle size, chemical composition, moisture, and volatile content among other parameters, influenced the tests carried out in this study. In order to properly assess the effect, dyes and cornstarch should be tested separately, so those parameters can be defined and the relationship between dyes addition and ignition sensibility and explosion severity can be assessed. Furthermore, testing dyes separately would allow the identification of those dyes that can lead to a greater explosion atmosphere. Manufacturers should consider this.

Nevertheless, from the ignition sensitivity and explosion severity results it was noticed that applied dyes produced significant differences in those parameters, and therefore, in their ignition and explosion associated risk. Furthermore, some samples presented low ignition values both for energy and temperature, which means that their use might require safety measures.

Overall, manufacturers 3,4 and 6 showed the most homogeneous results considering different colour results. However, manufacturers 2 and 5 showed important discrepancies especially when assessing MIE. Furthermore, those samples showed significant K_{st} discrepancies and 1 bar maximum pressure differences. Those differences cannot be explained by particle size as samples present similar average values, and neither by moisture as differences are noted in manufacturer 2 but not in number 5. From those results it can be deduced that discrepancies are produced by the ash content, as in both samples, greater ash percentage lead to higher flammable and explosion severity parameters.

3.4. Thermogravimetric analysis and differential scanning calorimetry

TGA results can be divided into two groups: samples that progressively lose mass when increasing temperature and samples that increase mass when increasing temperature. Those results are plotted in Fig. 3. On the other hand, DSC behaviour is similar for every sample, so DSC curves are plotted all together in Fig. 4.

As expected, the samples with higher ash content showed greater residue after thermogravimetric analysis. If the results from Table 5 are considered, it is expected that samples from manufacturers 1, 2 and 6 presented a typical organic material mass degradation, showing progressive mass loss due to temperature increase. However, manufacturer 2 samples behaved differently, which suggests that dyes affect the samples thermal behaviour. Indeed, the blue sample showed greater MIE and MITc than the green sample, but also lower Pmax and K_{st}. This fact is also noted in the TGA curves, as the blue sample behaves similar to

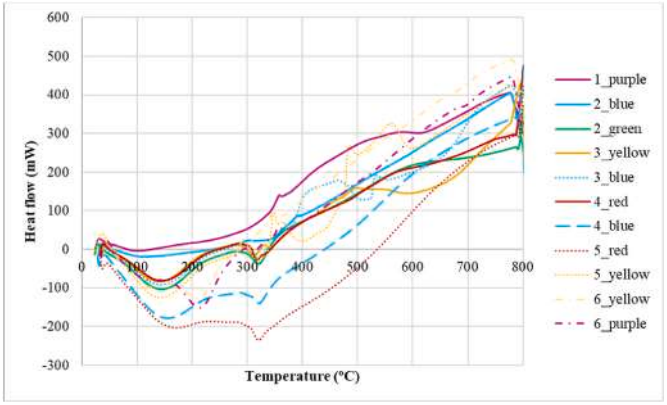

Fig. 4. DSC curves.

manufacturers 1 and 6 samples, while the green sample curve showed a mass increase as manufacturers 3, 4 and 5. Manufacturer 2 green sample showed a mass increase significantly lower than the remaining samples plotted in figure. As this sample also showed less flammability and explosive risk than samples from manufacturers 3, 4 and 5, it can be suggested that the noticed mass increase could be related to those parameters, therefore, it should be properly addressed.

According to the effects observed during ash analysis, an explosion was preliminary thought to happened. However, when carrying out STA it was noticed that the heat flow during mass increase was negative, in other words, the reaction was found to be endothermic, so no explosion nor deflagration was produced during the mass increase. Nevertheless, after the mass increase the reaction changed its tendency to higher heat flow values which indicates an exothermic reaction. For those samples that experimented mass increase, temperature at which mass began its increase (T_0), together with temperature at which mass reached its maximum ($T_{m,max}$) and the percentual mass increase can be seen in Table 6. Furthermore, heat absorbed (negative values) or released (positive values) during mass increase process can be calculated by integrating the heat flow curve and those values are also provided in this

Table 6
Mass increase STA values.

Manufacturer	Colour	T_0 (°C)	$T_{m,max}$ (°C)	Mass increase (%)	Heat (mJ)
2	Green	300.63	317.02	363.42	−622.19
3	Yellow	297.71	307.11	296.08	−316.75
3	Blue	305.65	315.03	887.89	−563.74
4	Red	300.95	310.96	2243.10	−934.12
4	Blue	309.42	316.95	692.37	−327.46
5	Red	305.21	315.13	2621.98	−792.82
5	Yellow	304.42	313.5	1892.57	−789.43

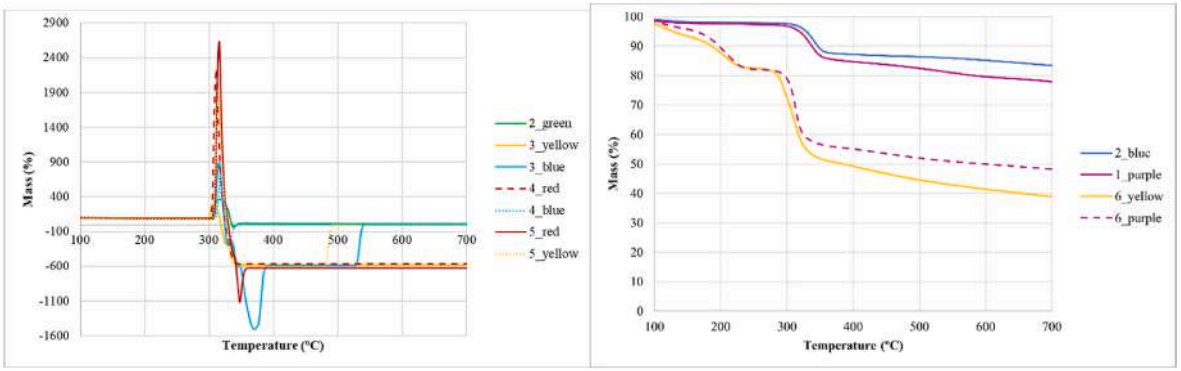

Fig. 3. TGA curves from 200 °C to 600 °C.

table.

According to the visual inspection carried out when heating the samples for ash content analysis, the mass of several samples increased. The powders behaved similar to yeast, releasing gases (mainly carbon dioxide and carbon monoxide) that were trapped inside the samples, so the external appreciation of the samples was similar to a film of mass that presents a porous material inside. It is possible that temperature increase led to the breaking of the sample and the release the gases inside the samples, and produced the explosion sounds together with the smoke that were observed during ash content analysis.

When considering samples that do not include inert materials in their composition, behaviour should be similar to previously published literature of corn-starch TGA (Athawale and Lele, 2000; Dai et al., 2019; Liu et al., 2009), however, results are completely different. This fact suggests that mass increase is produced due to dye addition. Indeed, when reviewing literature TGA curves, it can be noticed that reaction is similar to other organic materials, and slow mass decrease takes place beginning around 300 °C. However, manufacturers 3, 4 and 5 samples, together with manufacturer 2 green sample, also began the reaction at 300 °C, however, instead of mass loss, mass increase was produced.

From the obtained results, it can be noticed that samples required heat absorption in order to increase the mass, as all the heat values shown in Table 6 are negative and, therefore, endothermic reactions took place. However, Fig. 4 shows that after the endothermic reaction that leads to mass increase there is a change of tendency and the reaction turns to exothermic, which corresponds to the so-called explosion of the samples, when the mass molecules break and release the gases trapped inside.

Clearly, the higher the mass increase, the higher the heat absorbed. DSC plot shows that samples that increased mass, showed a heat flow negative peak around 300 °C while the others, showed a progressive increase as samples combustion releases heat. The dyes or the other additives in the samples that showed mass increase, seem to undergo an unexpected endothermic reaction with either nitrogen or oxygen at about 300 °C, before undergoing the expected combustion reaction.

Indeed, it can be seen that every sample presents a change of slope between 300 °C and 400 °C. The samples that did not produce mass increase are the ones that show better flammability and explosion severity results, which means that TGA analysis can provide preliminary information regarding samples characterization prior to carrying out the complete test procedures. The samples that presented a regular behaviour (mass progressively decreases) are the ones that presented higher ash content, which again, shows the importance of composition on those parameters.

Moreover, the samples that showed the greatest mass increase correspond to those that showed the highest $(dP/dt)_{max}$ values, so if several samples are tested and compared a correlation might be found, and preliminary behaviour predictions can be stated.

Nevertheless, the mass increase when performing STA was a non-usual result, as mass increase usually takes place when buoyancy effect is produced (Bottom, 2008; Menczel and Prime, 2009). Samples in a gas atmosphere can be subjected to a buoyant effect than can result in mass increase. However, buoyancy effect does not lead to a great mass increase percentage. Nevertheless, the present results show more than a 500% mass increase. Furthermore, from Fig. 2 it was noticed that volume increase took place around 300 °C, which could be related to thermal expansion, and it was a fast process, as the maximum mass percentage was reached after temperature increased ~10 K. Indeed, solids molecules have a reasonably fixed position within it, although each atom of the crystal lattice vibrates (and therefore moves), and the amplitude will depend on the total energy of the atom or molecule. When heat is absorbed, the average kinetic energy of the molecules increases and with it the average amplitude of vibrational motion and the combined effect of this increase is what gives the increase in body volume called thermal expansion.

As previously mentioned, after the thermal expansion, the sample begins to release heat producing an exothermic reaction that corresponds to the small explosion that takes place inside the sample when the molecules are broken, and the air is released. Because of that, the mass drops while changing the tendency of the DSC curve to higher heat exchange values. Considering that the thermal expansion was produced quickly, the fast volume increase could produce a serious buoyancy effect which completely destabilizes equipment balance and leads to mass negative values when buoyancy phenomenon is over. The observed phenomena suggest that two different stages in the reaction take place one after the other, but in a very short period of time. First, sample absorbs heat that produces thermal expansion and the mass increase by incorporating air bubbles. After that, temperature continues to increase producing molecule breaks in the sample which release the air inside the sample matrix producing an explosion that corresponds to the change from endothermic to exothermic reaction in the DSC results.

Moreover, according to the obtained results for different colours of the same manufacturer, suggest that oxidation of some of the inorganic dyes and pigments (or possible metals in the powder) can contribute to the mass increase noticed when performing TGA. This oxidation is also a fast process, whose characteristics meet the buoyancy effect, so a mix of both processes can occur. However, according to previously published literature, buoyancy effect is not as significant as thermal expansion.

4. Conclusions

Several samples were characterized in the present study. The screening test allowed to see differences between manufacturers and colours, which allowed estimating that dyes would affect flammability properties. Indeed, when carrying out ignition sensitivity and explosion severity characterization, those differences were remarkable, and also dye effects.

The results provided in this research can be very useful as it characterizes different samples and parameters, comparing compositions, physical parameters such as particle size, and flammability characterization. It was noticed that proximate analysis provides important information, as the ash content heavily influenced explosion severity results.

The use of Coloured powder (Holi powder) constitutes a serious risk when dispersed in enclosed spaces, as it produces a dust explosive atmosphere. Furthermore, the ignition conditions of these atmospheres are not very demanding, and therefore, an explosion or flash fire can be inadvertently initiated. It was noticed that manufacturers did not take this fact into account as the safety recommendations seem not to consider the further consequences that could happen if used in a confined space. Its flammable nature should be addressed and indicated in the package instead of avoiding this information. Furthermore, labels as the one provided by manufacturer 2, whose package specified “non-flammable”, should be corrected, as the obtained results differ from this statement, which may incur into fatal accidents. Some safety suggestions that should be included in the package are as follows: “To use in open air”, “Not designed for use in small, confined and poorly ventilated spaces, due to its flammability”, “Keep away from sources of ignition and heat” and other recommendations about health or air quality, as their use could be harmful and toxic. Furthermore, when comparing the samples with previously published literature, it was noticed that manufacturer 2 samples and one sample from manufacturer 3 presented lower ignition parameters than corn-starch. Although this parameter depends on different properties besides composition, the dye addition might increase the risk of this material.

Due to the tests carried out in this study, it was noticed that some manufacturers (1 and 6) presented higher ignition parameters, so the flammable conditions are more difficult to reach. Both manufacturers included inert materials in the powders composition (talcum and sodium bicarbonate respectively). The addition of inert materials into the powder composition produced the ignition parameters increase, which means that manufacturers that incorporate inert materials to corn-starch

produce a safer coloured powder. Between both manufacturers that meet this condition, manufacturer 1 showed better results, which means that talcum addition better reduces ignition than bicarbonate and sodium chloride, and high ash content reduces explosion risk. Although this study has focused on air dispersion in order to produce dust clouds, TGA and ash content analysis were carried out on non-dispersed samples. Furthermore, an initial relationship between TGA and explosion rate was found, so further studies could focus on a better definition of this relation.

From TGA tests it was noticed that around 300 °C the dust undergoes thermal expansion which rapidly enlarges volume. This fact should also be addressed, and coloured powder safe storage conditions should be defined in order to avoid accidents due to thermal expansion.

The present study reported considerable data regarding the composition and behaviour of coloured powders. Moreover, the findings of the present study allowed to define the explosive and flammable tendency of the dusts. These findings can be useful not only for colour powder use but also for production, in order to produce a safer powder.

CRediT author statement

Conceptualization:IAA, BCS. Methodology:IAA, BCS, DLR. Software: BCS; DLR. Validation:BCS, DLR. Formal analysis:BCS, IAA. Investigation:IAA, BCS, DLR. Resources:JGT. Data Curation:BCS, IAA. Writing - Original Draft:IAA, BCS, DLR. Writing - Review & Editing:JGT. Visualization:BCS, JGT. Supervision:JGT.

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.

Data availability

The authors do not have permission to share data.

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