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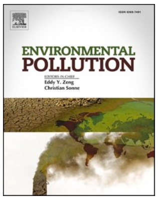

Assessment of sustainable compositions to reduce emissions and sound pressure level of flash powder☆

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ABSTRACT

Flash powder, an explosive compound widely used in flash bangers and pyrotechnic shells, among others, has emerged as a critical point in discussions about the negative effects of its use. Currently, fireworks present significant challenges due to their adverse impacts on the environment and the generation of acoustic disturbances in residential and urban areas due, among other compounds, to flash powder. This powder, mainly composed of potassium perchlorate and metallic compounds such as aluminium or magnesium, is crucial to achieve the opening and bursting of pyrotechnic devices. Therefore, it is necessary to develop alternatives that solve the flash powder associated problems to give a sustainable future to the pyrotechnic sector. This study proposes compositions that could be possible alternatives to reduce emissions and sound pressure levels, whit the intention of ensuring suitable performance for these pyrotechnic articles. F2 category flash bangers from different manufacturers were collected. The operation of these bangers was compared in different tests, by adding inert materials such as sodium bicarbonate ($NaHCO_3$) and recycled glass, at 10 % and 20 % (w/w), and by replacing the flash powder with nitrocellulose ($[C_6H_7(NO_2)_3O_5]n$), with a nitrogen percentage of less than 12.6 %, as stated in the European pyrotechnics regulation. The samples were subjected to sound pressure level measurements according to EN 15947–4:2022 standard, but also CO and CO_2 emissions were evaluated. It was observed that the compositions studied could lead to a significant reduction in both pollutant emissions and the noise level generated by the pyrotechnic articles. After studying the explosion pressure generated for their substitution in pyrotechnic shells, it is concluded that the addition of inert compounds can be a real alternative. However, the nitrocellulose does not achieve a correct operation as a substitute for flash powder, and nitrocellulose with a higher nitrogen content must be studied.

1. Introduction

The attractiveness of pyrotechnic shows, which in several cultural traditions and celebrations can be considered as a base root, is now facing challenges due to the environmental impact (Chen et al., 2022; Gonzalez et al., 2022; Greven et al., 2019; Nasir & Brahmaiah, 2015) and acoustic disturbances (Lombera et al., 2023). The widespread use of flash powder, one of the main components in pyrotechnic devices, has been identified as a significant contributor to these challenges, which leads to the need to explore sustainable alternatives. As several studies point out (Moreno et al., 2010; Sijimol & Mohan, 2014), the adverse effects emphasise the urge to mitigate the impacts associated with pyrotechnic events.

Flash powder is primarily composed of potassium perchlorate and metallic compounds (Russell, 2009), and plays the main role in achieving the spectacular sound effects of pyrotechnic shows. However, its association with environmental pollutants and high sound pressure levels requires innovative solutions for the continued viability of the pyrotechnic sector. In recent years, different alternatives have been studied (Azhagurajan et al., 2019; M. Rajendran et al., 2021) and visual shows have even been designed with other types of technologies (Vergouw et al., 2016), but lacking the essence of pyrotechnics.

Nitrogen-rich compounds could be a solution. In the past years, the use of nitrocellulose in the pyrotechnic sector has increased

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significantly, especially in some devices that are currently using nitrocellulose as their main component. Based on the use of nitrocellulose as a propellant for different types of ammunition (Yolhamid et al., 2018), pyrotechnic devices such as fountains or table bombs, intended for indoor use, use nitrogen-rich compounds in their composition, according to the standard (EN 15947-4, Pyrotechnic Articles - Fireworks, Categories F1, F2, and F3 - Part 4: Test Methods, 2022). The use of nitrocellulose in pyrotechnic devices presents significant advantages that establish nitrocellulose as a viable substitute for flash powder. The most notable advantage lies in its potential to reduce environmental impact compared to traditional explosive compounds like flash powder, mainly because it removes metal compounds. According to toxicological research, it has been shown many of the metalliferous particles in fireworks smoke are reactive and can affect human health (Moreno et al., 2007). Additionally, nitrocellulose presents a cleaner combustion (Espinoza & Thornton, 1994; MacCrehan et al., 2002), generating less particle emissions and potentially lowering the overall environmental footprint of pyrotechnic shows. Still, the environmental advantages are tempered by challenges associated with nitrocellulose, as the production process of nitrocellulose involves the use of nitric acid and other nitrogen compounds (Jamal et al., 2020; Mattar et al., 2020), which present environmental implications, raising concerns about pollution. The content of nitrogen is an essential parameter in nitrocellulose pyrotechnic devices, as it directly influences their performance and safety. With a nitrogen content below 12.6 %, nitrocellulose is more stable and less explosive (Chai et al., 2020), making it suitable for pyrotechnic applications such as fireworks, providing rapid combustion and vibrant colours without compromising safety (Dejeaifve et al., 2018).

Therefore, while nitrocellulose presents potential benefits for reducing some of the most important environmental impacts during pyrotechnic events, a comprehensive assessment of its use as a substitute needs to be carried out in order to determine if the environmental challenges are properly addressed and correct performance of the devices is achieved. Furthermore, the substitution of flash powder with nitrocellulose may require adjustments to the formulation to achieve comparable sound and visual effects, since the absence of metallic compounds in their composition prevents the principle of flash luminous effects due to lower temperature combustion.

Because of that, this study endeavours to address these concerns by proposing alternative device designs that not only maintain the performance standards of pyrotechnic articles but also significantly reduce emissions and noise levels. In addition to nitrocellulose, the implementation of inert compounds in flash powder is being studied for this purpose. The storage of pyrotechnic material can pose a high risk of accidents if the necessary measures are not taken (León et al., 2023). Therefore, the addition of these compounds presents safety improvements for explosive dust, as it is an effective way to reduce the risk of explosion and sensitivity to ignition (Amez et al., 2023; Bu et al., 2020). Furthermore, inert materials reduce the environmental emissions generated in the combustion of different fuel compounds (Guerrero et al., 2021; Hudák et al., 2021). Inert compounds act as diluting agents, lowering the concentration of reactive species in the combustion zone. This reduces the reaction temperature and slows down the rate of combustion, leading to a decrease in the formation of intermediate species. In addition, these materials absorb part of the heat released, increasing the minimum ignition energy (MIE), minimum ignition temperature (MIT) and thus reducing the energy released (Addai et al., 2016). The present research focuses on F2 category flash bangers from various manufacturers as representative samples. The test methodology focuses on involving the addition of inert materials and the substitution of flash powder with nitrocellulose, to study whether it is possible to optimize the composition of pyrotechnic devices without losing the visual and sound effects but reducing their negative impact.

The evaluation criteria extend beyond conventional sound pressure level measurements, encompassing the assessment of CO and CO_2 emissions. Carbon monoxide (CO) and carbon dioxide (CO_2) are two of the main combustion products of pyrotechnic compositions and can have significant adverse effects on air quality and human health. CO is a toxic gas that can cause poisoning when inhaled in high concentrations (Huzar et al., 2013), while CO_2 is a greenhouse gas that contributes to global warming and climate change (Edenhofer, 2015). Another key factor of flash powder is the pressure it generates inside the container, which allows the release of a shock wave with sufficient energy to cause the explosion or opening of the pyrotechnic device (A. J. Rajendran & Thanulingama, 2008). If the overpressure achieved by the combustion of the explosive powder is not sufficient, the pyrotechnic device will not work correctly. In this case, the application of these alternatives in pyrotechnic shells, a ubiquitous element in displays, would not be feasible, because this device needs to achieve a correct opening in the air to trigger the desired visual effect (Russell, 2009). Addressing this critical requirement, which also involves the achievement of optimal opening heights, the measurement of explosion wave pressure and establish a preliminary relationship between Net Explosive Content (NEC) – Explosion pressure are the main objectives.

2. Materials and methods

The data collection process encompassed meticulous recording of CO and CO_2 emissions, sound pressure levels, and shockwave pressures for each busting charge type. All the equipment used in the study belongs to the Laboratory of Gas Detectors of the TECMINERGY - Laboratorio Oficial J.M. Madariaga (LOM) and is correctly calibrated, verified and in optimum condition for use at the time of the tests.

2.1. Samples

The objective of this study is to conduct a comprehensive comparative analysis of traditional flash powder commonly employed in pyrotechnic applications and possible alternatives. To achieve this objective, a meticulously designed experimental setup was used to analyse gas emissions, sound pressure levels, and overpressures generated by each bursting charge type. The investigated compositions comprised flash powder, consisting of a mixture of perchlorate and Al/Mg, nitrocellulose-based charges, and flash powder by adding inert compounds, such as recycled glass and sodium bicarbonate, with concentrations of 10 % and 20 % (w/w). The main fireworks using flash powder are flash bangers and shells (Kosanke & Weinman, 2012). Due to the complexity of the shells and their large NEC, all these compositions have been studied in three different F2 category bangers, as described in Table 1, which comply with the requirements set out in EN 15947–5:2022 (EN 15947-5, Pyrotechnic Articles - Fireworks, Categories F1, F2, and F3 - Part 5: Requirements for Construction and Performance, 2022).

In order to test the compositions under study in the three different bangers, it was necessary to remove the initial composition and fill it with the target composition and the same load. The new banger charge is now called New Net Explosive Content (NNEC). For this purpose, one of the gypsum plugs was removed from the container tube, which will be rebuilt after the tube has been filled. Fig. 1 shows a diagram of the process used to fill the compositions to be studied.

Table 1
Samples of category F2 flash bangers.

Samples	Type of article	Composition	Category	NEC (g)	Tube dimensions (mm)
A	Banger	Perchlorate/ metal	F2	0.08	Ø6 × 35 mm
B	Banger	Perchlorate/ metal	F2	0.1	Ø7 × 40 mm
C	Banger	Perchlorate/ metal	F2	0.2	Ø9 × 30 mm

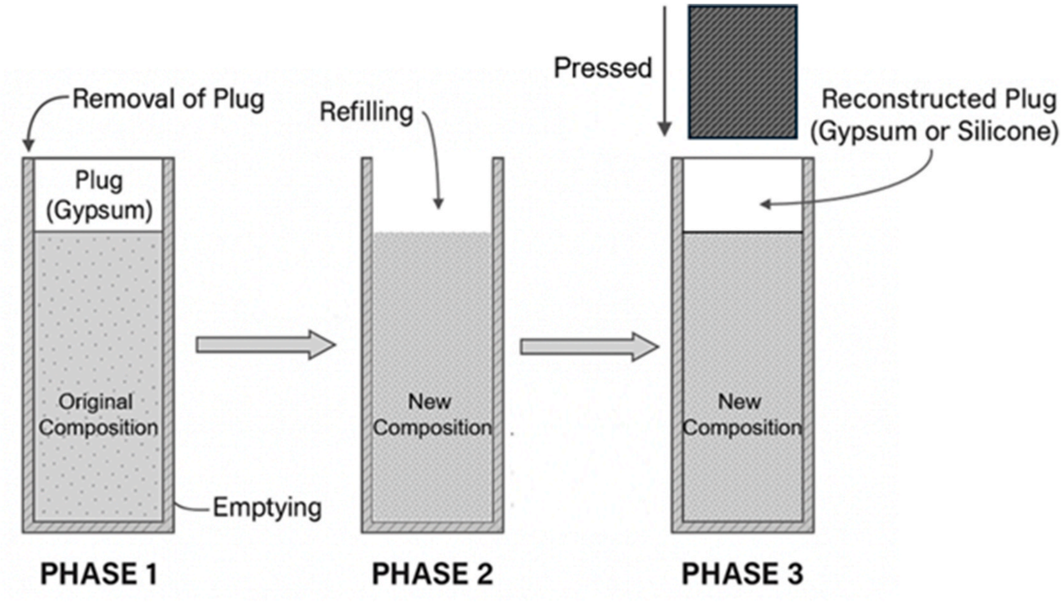


Fig. 1. Diagram of the composition substitution process.

First, the plug was removed from the back of the container tube and the original composition was emptied. Then, the tube was refilled with the same total load using the compositions under study, which can be seen in Table 2. Finally, the back plug of the flash banger was reconstructed with gypsum or silicone, depending on the test. During the reconstruction of the plug, it was manually pressed with a solid tube of smaller diameter than the container tube. It is necessary to test the compositions inside these bangers because the pressure generated inside the tube by the gases released during the combustion of the powder is responsible for the opening of the tube and thus the bursting effect. All the compositions were tested under the same conditions for each analysis to obtain a real comparison.

A certain flash powder composition, with 80 % $KClO_4$ and 20 % Al, was tested as a reference. In addition, two different types of nitrocellulose from the same supplier with different qualities were compared. According to the supplier, white nitrocellulose had a higher purity and a lower content of organic residues, whereas yellow nitrocellulose contains higher impurities derived from its synthesis. Finally, different concentrations of inert compounds were added to the reference flash powder. In particular, sodium bicarbonate with less than 300 μm and recycled glass with less than 700 μm were used, with concentrations of 10 and 20 % (w/w). $NaHCO_3$ is one of the most studied and commercially available inert materials and recycled glass contributes to the circular economy of glass, promoting sustainability and minimizing waste and emissions.

2.2. Assessment of CO and CO_2 emissions

Some of the most polluting and harmful compounds in pyrotechnic mixtures are perchlorates and metalliferous particles (Steinhauser & Klapötke, 2008). In addition, other important levels that directly or indirectly influence the greenhouse effect must be considered (Ambade, 2018). Gas emission analysis was conducted using an Emerson XStreamIR continuous gas analyser, capable of accurately measuring CO_2 emissions in % vol. and CO emissions in parts per million (ppm) from an inlet flow rate.

Bursting compositions were ignited within a controlled environment to facilitate the capture and subsequent analysis of gas emissions. In order to have a verification of accuracy, before carrying out the tests, the values measured by the analyser were checked using a 300 ppm CO gas bottle and a 20 % vol. CO_2 gas bottle.

Two tests were conducted for each composition and sample, each involving one banger, to ensure accurate measurements. Fig. 2 shows a flowchart of the measurement system.

Samples were placed inside a 10L reactor, and once the fuse of the pyrotechnic article was ignited, the reactor was sealed before gas release began. This ensured that gases generated by the devices remained inside the reactor. These gases include emissions from both the combustion reaction of the banger and the protruding fuse, although the latter's contribution is minimal compared to other emissions. The gas analyser's inlet flow was connected to the sealed reactor by a suction tube and the gases were extracted thanks to the analyser's pump through this tube. A valid measurement of CO and CO_2 was determined once stabilisation occurred. Notably, the inlet flow to the analyser also includes gases trapped in the reactor's closed atmosphere (air atmosphere), simulating real-life conditions where pyrotechnic devices are discharged in open environments. To prevent measurement interference, the reactor was opened and cleaned with an air compressor after each test, and analyser measurements were held until returning to the initial zero value.

Table 2
Composition of bursting charges tested.

Abbrev.	Type	Composition
FP	Flash powder	Perchlorate/metal
YN	Nitrocellulose	Yellow Nitrocellulose
WN		White Nitrocellulose
10B	Flash powder with inerts	10 % Sodium Bicarbonate
20B		20 % Sodium Bicarbonate
10G		10 % Glass
20G		20 % Glass

2.3. Sound pressure level measurements

Fireworks, mainly those using flash powder, reach sound pressure levels that, although within the safety limits of human hearing, can be annoying to urban residents (Kukulski et al., 2018). Sound pressure levels produced by the different bursting charges mentioned above were measured. The sound level meter used in the tests was the Brüel & Kjaer model 2250-L portable analyser. This equipment complies with the IEC 61672-1 standard, as it belongs to class 1 and has a 4950-type open field microphone. It is also equipped with a ZC-0032 preamplifier. These measurements were taken following the established pyrotechnic EN

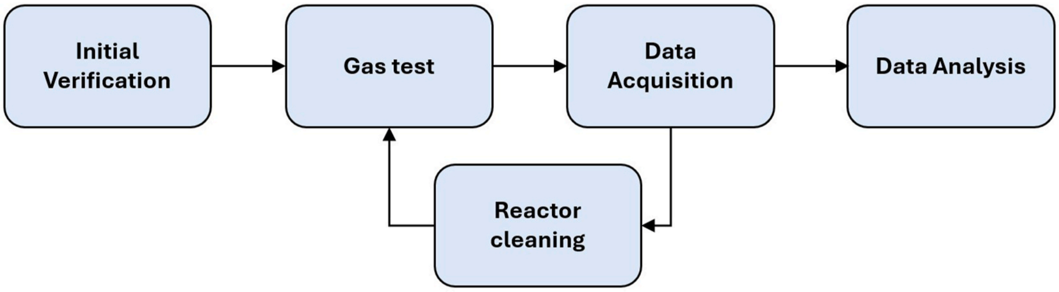


Fig. 2. Flowchart of emission assessment tests.

15947–4:2022 standard, ensuring compliance with prescribed distances for F2 category articles (8 m), on a concrete surface and using a digital anemometer to measure wind speed and ambient temperature. The sound level meter was placed on a tripod so that it was stable and at a height of 1 m above ground level, as can be seen in Fig. 3.

The sound level measurement scale was the one used in fireworks measurements. The A-weighted scale and the maximum impulsive level were used, resulting in measurement values in dB (AImax). In order to carry out these tests and to obtain greater reliability, 5 bangers were fired with each of the compositions under study, which means a total of 35 samples for each banger. For these tests, as for the assessment of emissions, silicone was used to reconstruct the sealing plug of the container tube once it had been filled with the composition under study.

2.4. Explosion pressure analysis

The compositions studied must not only reduce pollutant emissions and sound pressure levels to be viable alternatives but also ensure the proper functioning of pyrotechnic devices. For this reason, shockwave pressures generated by the bursting charges were meticulously assessed by the design of an explosion pressure measurement equipment. The diagram of this equipment is shown in Fig. 4.

The explosions were conducted in a cylindrical flameproof vessel with an internal volume of 360 cm^3, certified with the European marking for equipment in the presence of explosive atmospheres as *EEx d IIC T6*. A piezoelectric pressure transducer, model KISTLER 601CAA, was coupled directly to the vessel and exposed to the internal atmosphere. This transducer converts pressure into an electrical signal, by a measurement range of 0–250 bar, which ensures adequate coverage for the maximum expected overpressure values during the deflagration of pyrotechnic compositions. The electrical signal generated by the transducer was amplified and conditioned by the KISTLER 5039A312 amplifier and then digitalised using a high-speed data acquisition (DAQ) system operating at a sampling rate of 100 kHz. The digitalised data were recorded and analysed using an appropriate software, enabling the visualisation of pressure-time curves, the calculation of maximum pressure (P_{max}) and pressure rise rate (dP/dt). The bangers were fired within these controlled environments, and pressure data were meticulously recorded for subsequent analysis.

For these tests, again two bangers are fired for each of the different compositions and samples. The difference with the bangers tested so far is that this time, it is necessary to remove the protruding fuse. The fuse is

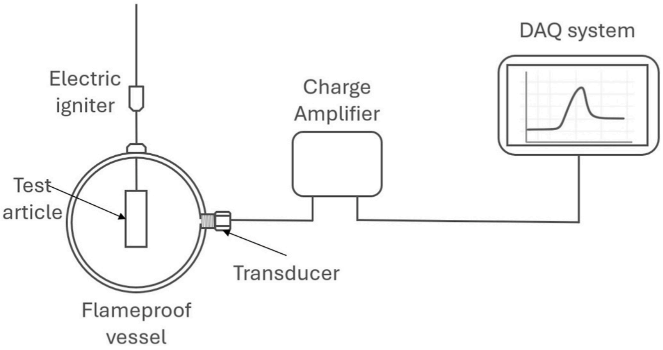


Fig. 4. Schematic of the explosion pressure measurement system.

Fig. 3. Sound pressure level test setup.

replaced by an electric igniter because the analytical equipment is designed to send an electrical signal when the measurement is initiated. Moreover, due to the delay of the fuse, it is unfeasible to use this means of ignition, since the explosion of the banger would occur outside the measuring range captured by the equipment (500 ms after activation). Furthermore, to adapt the banger with the new compositions to real situations and thus be able to study their possible use as a substitute for flash powder, the plugs were rebuilt with gypsum.

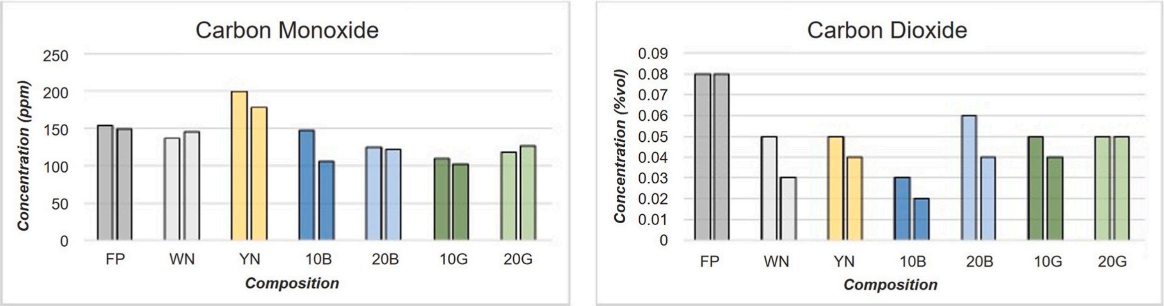
3. Results and discussion

3.1. CO and CO_2 concentration of the released gases

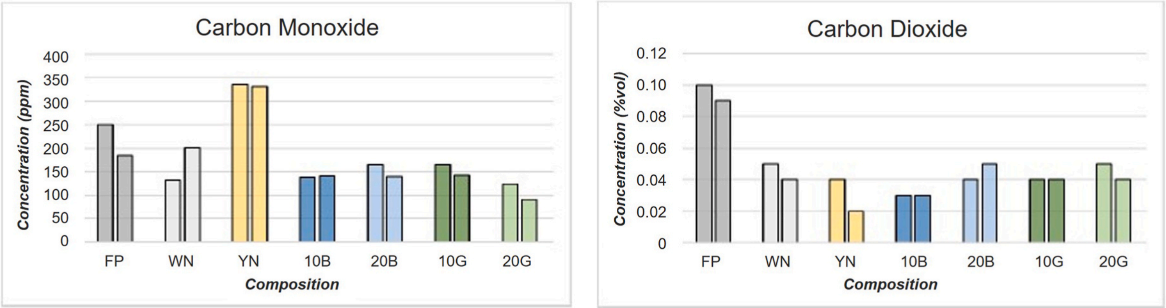
The emissions assessment carried out during the combustion of the different compositions and samples studied in air atmosphere at 16 °C allows a comparison of the carbon monoxide and carbon dioxide generated by each of them. Fig. 5 shows the results recorded by the gas analyser for the three types of flash banger (Sample A, B and C) and the different compositions under study, which are defined in Table 2. The concentrations of CO and CO_2 obtained for the two samples tested for each of the compositions and bangers are shown below.

These results offer remarkable conclusions about the emissions of gases such as CO and CO_2 released by flash powder and their possible alternatives studied. According to previous studies about firework emissions (Gonzalez et al., 2022; Karuppasamy et al., 2024; Pathak et al., 2013), it is observed that as the NNEC contained in the banger increases, the emissions of both gases also increase. This can be seen in the noticeable increase in the values in Fig. 5 as the total charge of the sample increases. For samples A, which have 0.08 g of NNEC, the maximum concentrations reached are 199 ppm CO for the yellow nitrocellulose composition and 0.08 % vol. CO_2 for the original flash powder composition. The maximum values for the B samples are obtained at the same compositions, but in this case, since 0.1 g of NNEC is used, the measured values are 336 ppm and 0.10 % vol. of CO and CO_2, respectively. Finally, for the samples C using 0.2 g of NNEC, the highest concentrations of both gases are obtained. Again, the maximum carbon monoxide value appears in the yellow nitrocellulose, but this time with 1612 ppm. On the other hand, 0.29 % vol. CO_2 is the maximum concentration of this gas reached for the original flash powder. As shown, the emissions released after the combustion of the different

Samples A emissions



Samples B emissions



Samples C emissions

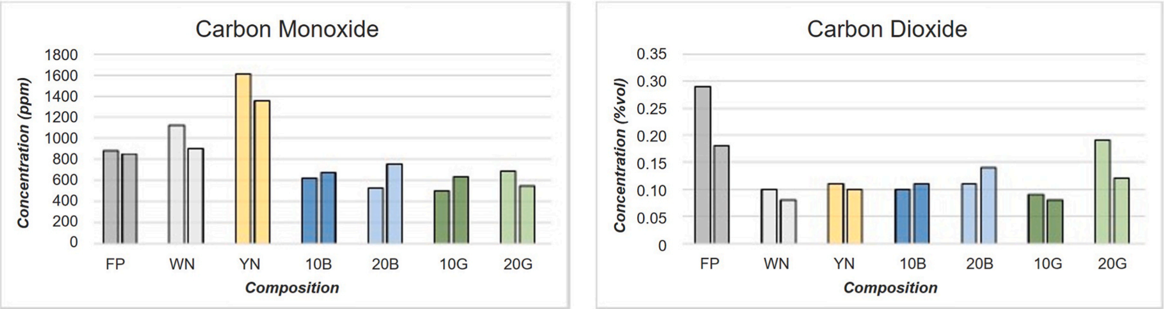


Fig. 5. Emission test results.

compositions are directly related to the NNEC amount used in the bangers.

Comparing each of the compositions used in the different samples (A, B and C), it can be seen that the three different types of bangers follow the same trend. Focusing on the carbon monoxide emissions released, this is one of the main products of nitrocellulose combustion because the composition was not fully oxidised, probably due to lower combustion temperatures or less aggressive reaction kinetics (Dauerman & Tajima, 1968; Finnerty et al., 1992). It is clear that yellow nitrocellulose generates higher concentrations of this gas. White nitrocellulose, which has a higher purity, burns cleaner and more efficiently, so carbon monoxide emissions are lower and comparable to those of flash powder. According to the average values recorded for each sample and composition, yellow nitrocellulose emits 25–95 % more CO than flash powder and white nitrocellulose. This is due to impurities in the composition, which affect emissions. Moreover, nitrocellulose has been extensively studied and previous research has found that the use of this compound produces nitrogen oxides, a by-product that was not found in flash powder compositions (Guidotti, 1980; Szostak & Cleare, 2000). Nitric oxides cause significant environmental problems, such as acidification, eutrophication and toxicity, among other effects (Van Vuuren et al., 2011). By adding inert compounds such as sodium bicarbonate and recycled glass, a decrease in CO emissions is observed. This decrease was foreseeable, since by adding inert and still using the same total amount of mass inside the banger (NNEC), the amount of NEC decreases, because inert compounds act as diluting agents. Values close to 50 % of the emissions generated by the reference powder can be observed for the 20 % by mass recycled glass compositions for samples B, which reduce average CO emissions from 217 ppm to 106 ppm. Forecasts indicated that the higher the amount of inert material, the lower the emissions should be, but this is not always the case. Concentrations from the combustion of compositions with 20 % (w/w) recycled glass are observed to generate higher emissions than those with 10 % (w/w). The same fact applies to sodium bicarbonate. This could be due to the loss of moisture and carbon dioxide that has been observed in previous studies during the thermal decomposition of inert (Ball et al., 1986). Further studies should consider carry out a larger number of tests with these compositions and to see average values, as these punctual deviations may also be due to the protruding fuse emissions or to residues of the initial composition in the container tube.

When looking at carbon dioxide emissions, it can be seen that in this case, traditional flash powder is the one that generates the highest concentrations of this gas. By adding inert and reducing the NEC, as with CO emissions, carbon dioxide emissions decrease. The resulting CO_2 emissions for such compositions are even lower than 50 % of the flash traditional powder in some cases. For example, the average emissions generated by the 10 % by mass sodium bicarbonate compositions for samples A reduce CO_2 concentrations from 0.08 %vol. to 0.03 %vol. In contrast to carbon monoxide emissions, nitrocellulose (both yellow and white) also generates less carbon dioxide emissions than flash powder. This is one of the great advantages of this compound, because although carbon monoxide emissions may be higher if low-quality nitrocellulose is used, carbon dioxide emissions are always reduced. It is important because CO_2 has a direct influence on climate change, while CO only has an indirect influence and has a much shorter residence time in the atmosphere (Liu et al., 2021). However, the most important advantage of this compound is the elimination of residues derived from perchlorate, the most harmful compounds in pyrotechnics (Wilkin et al., 2007), reduction of metalliferous particles contained in the flash powder (which are reduced for any of the alternative compositions studied) and the removal of soot generated by traditional powder (Munroe, 1896; Petty, 1969), thereby achieving greater clarity in the pyrotechnics effects (Dejeaifve et al., 2018).

3.2. *Sound pressure level*

As previously pointed out, one of the great concerns of today’s society in relation to fireworks is the annoyance caused by the sound pressure levels resulting from the bursting effects. Because of that, these tests measure the sound pressure level reached by the different compositions under study, in order to check if it is possible to reduce it while maintaining the correct performance of the pyrotechnic devices. As mentioned before, each test was repeated 5 times, therefore the mean values obtained for the sound pressure levels of each of the bangers and compositions under study are shown in Fig. 6.

The sound pressure level tests were carried out at a temperature of 4.8 °C, a relative humidity of 70 % and a wind speed of 2.125 m/s in the NE direction, favouring the transmission of sound towards the sound level meter. According to (Attenborough, 2014), climatic conditions have an influence on sound propagation, but for this test these conditions were constant, so the results are comparable with each other.

As can be seen in the results obtained, the highest sound pressure level values are obtained for bangers using traditional flash powder. For sample A, the mean obtained is 114.85 dB (AImax). Sample B, which has a higher NNEC, reaches an average sound level of 114.03 dB (AImax). Finally, sample C, with an NNEC of 0.2 g per banger, reaches a mean value of 117.13 dB (AImax). It is shown that the sound pressure level does not depend only on the NNEC contained in the banger, since sample A with a lower NNEC than sample B achieves higher noise levels. This trend in noise levels continues for all the tested compositions of bangers A and B, so it is proved that other factors such as the design, bursting strength of the paper used for the container tube or the compression generated by the gases released also have a great influence on the sound levels reached (A. J. Rajendran & Thanulingama, 2008).

For each of the bangers tested, it is shown how the addition of inert compounds such as sodium bicarbonate and recycled glass reduces the sound pressure level reached. As the literature indicates, inert compounds absorb part of the heat released in the combustion reaction and thus reduce the energy released, thereby lowering the sound pressure level emitted. Sodium bicarbonate is found to be more effective in reducing the bursting noise generated by the banger. This differs from results obtained by other researchers. According to (Castells et al., 2024), both inert compounds show similar effectiveness when comparing their influence on the thermal properties of biomasses. This shows that the explosion pressure and the generated sound effect are not necessarily directly related to the thermal properties. Furthermore, as expected, noise levels are lower when using inert concentrations of 20 % (w/w) instead of 10 % (w/w). The lowest sound pressure level is recorded for each of the bangers when testing the composition composed of flash powder and 20 % sodium bicarbonate. A mean of 107.37 dB is recorded for sample A. Sample B gives an average of 105.61 dB and the average sound pressure level for sample C is 111.24

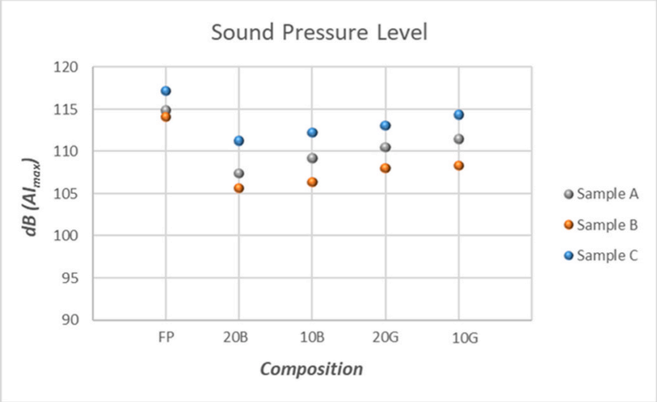


Fig. 6. Sound pressure level test results.

dB. With this type of composition, the noise level is reduced by 5–7 %. As the decibel scale measures the sound pressure level on a logarithmic scale of base 10 (Roberts, 1984; Young, 1971), this decrease in decibels actually means a very important reduction in the perception of the ear. The decibel reductions achieved for the 20 % sodium bicarbonate compositions are close to 10 dB, which represents a reduction in hearing response of about half. In other words, concentrations of 20 % sodium bicarbonate reduce the perceived sound by approximately 50 %. This remarkable noise reduction may not be ideal for customers of flash banger, whose main effect is the production of flash and sound, but could be an important solution for pyrotechnic shells, whose main effect is the production of colour and visual effects and the accompanying sound, in many cases, is an undesired effect as a consequence of the opening of the article.

For the two types of nitrocellulose (white and yellow) tested in the three different bangers, a correct performance is not achieved. In all of them, the banger does not break the cardboard that makes up the container tube, and therefore, the desired bursting effect does not occur. The nitrocellulose reacts but releases the gases generated by the silicone plug instead of breaking the cardboard. This is because nitrocellulose does not react as violently as flash powder. Flash powder is mainly composed of a strong oxidiser together with a reducing agent, such as aluminium powder. These ingredients react very quickly when ignited, resulting in instantaneous combustion and rapid energy release (Chapman & Howard, 2010; Kosanke & Weinman, 2012). On the other hand, nitrocellulose burns more slowly compared to flash powder (Oxley, 1993; Zel'dovich, 1942). To estimate the influence of the material used as a plug in the container tube, further tests should be carried out with gypsum plugs in an attempt to withstand the generated overpressure and to analyse whether in this way the nitrocellulose bangers would succeed in breaking the cardboard tube.

3.3. *Explosion pressure analysis*

The explosion pressure generated by bursting charges is one of their main characteristics. This powder is characterised by a high reaction speed and high temperatures due to the metallic compound (Kosanke & Weinman, 2012). This quickly generates a large quantity of gases that increase the pressure inside the container until it breaks and the explosion occurs. Therefore, it is possible to represent the phenomena as an explosion pressure (kPa) - time (ms) curve, as shown in Fig. 7 for a sample A banger with flash powder composition tested.

The pyrotechnic shells have a small container with flash powder inside. Once the desired height is reached, the flame communicates with this flash powder and the device opens, transmitting the flame to the main effects of the shell (coloured stars, cracker, sound effects, etc.) (Lancaster, 1998). Thus, it is noted that the aim of the flash powder is different when used in bangers or shells. Therefore, in order to be able to apply the alternatives studied in pyrotechnic shells, it is necessary to analyse the explosion pressure to study whether it is feasible to achieve the opening of the device. The results of the explosion pressure measurement tests are shown in Table 3. The temperature conditions during the measurements vary between 12.5 °C and 13.4 °C.

According to the results obtained, some of them are discarded due to failure or malfunctioning of the banger. In particular, for all the nitrocellulose bangers tested (except WN in sample A), the powder is flamed but does not break the carboard tube, as noticed in previous tests. This is because they do not react as violently and instead of achieving a bursting

Table 3
Maximum explosion pressure registered (kPa) in an explosion chamber of 360 cm^3.

	Sample A	Sample B	Sample C
FP	320.0	512.0	555.9
FP	331.6	476.4	589.9
WN	14.4	–	–
WN	27.5	–	–
YN	–	–	–
YN	–	–	–
20G	228.6	353.6	497.3
20G	239.5	240.8	539.6
10G	311.2	404.2	542.3
10G	291.5	411.7	533.4
20B	132.7	297.8	466.4
20B	234.7	284.1	423.2
10B	272.1	427.3	520.8
10B	257.1	369.8	508.6

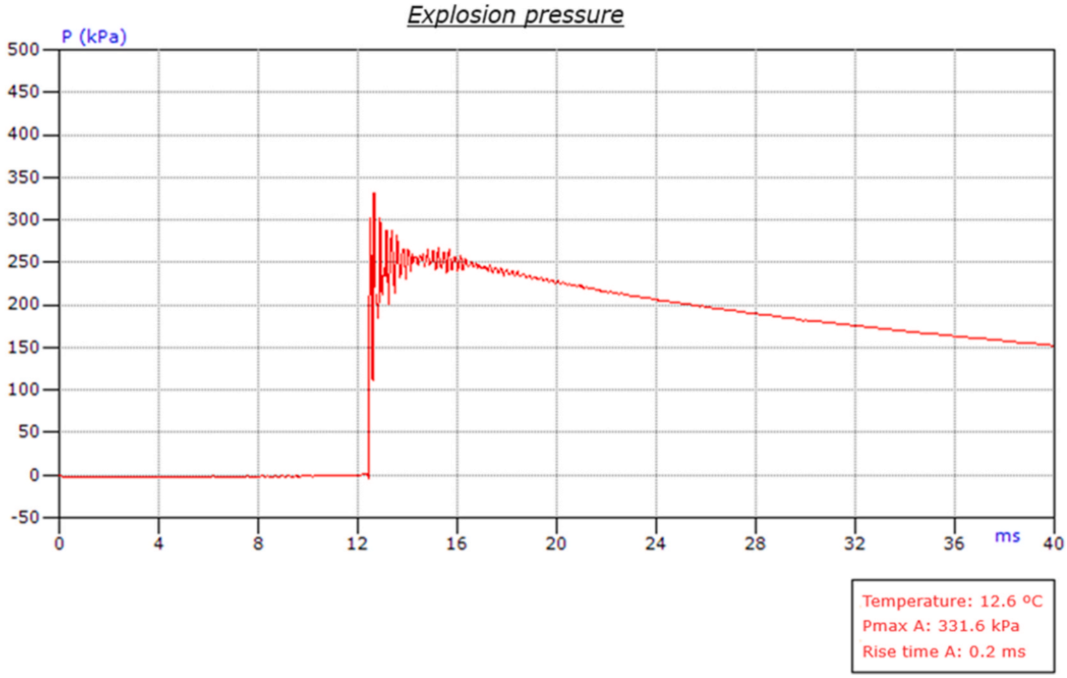


Fig. 7. Explosion pressure curve generated by sample A banger with flash powder composition.

effect by breaking the cardboard, a more continuous effect is achieved as the gases are gradually released through the plug. Although the bursting effect is achieved for the WN of the A samples, it is noted that the pressures achieved are very low compared to traditional flash powder. Partial substitution to conserve in the composition metallic particles or increasing the nitrogen content of nitrocellulose would result in a higher reaction rate and an increase in the heat of the reaction (ΔH) and thus a more explosive character (Cieślak et al., 2021), but its safety conditions would be worsened, due to the decline of the thermal stability (Chai et al., 2020; Pourmortazavi et al., 2009) and the critical explosion temperature (Tb) (Chai et al., 2019). However, previous research already reported improvements in nitrocellulose thermal stability by increasing the moisture content (Wei et al., 2018).

For bangers composed of the original flash powder and the samples with inert composition, a correct performance is achieved. As can be seen, generally the explosion pressure generated increases as the NNEC also increases. However, its relationship is not directly proportional. Using average values measured for the flash powder samples, it can be seen that sample A (0.08 g NEC) generates an explosion pressure of 325.8 kPa. Sample B, which contains 0.1 g of NEC, releases an explosion pressure of 494.2 kPa. Finally, sample C, which has twice the NEC of sample B, only generates 16 % more pressure, i.e. 572.9 kPa. This shows that the NNEC is not the only factor influencing the explosion pressure. Other factors such as design, tube material or volume of the container also influence this pressure (A. J. Rajendran & Thanulingama, 2008), as was noticed when addressing the noise level tests.

It can be seen in Fig. 7 that, using a 360 cm^3 explosion chamber, there is a sudden pressure increase reaching a maximum pressure of 331.6 kPa in just 0.2 ms. This represents a maximum rate of pressure rise $(dP/dt)_{max}$ for this sample of 1658 kPa/ms. The $(dP/dt)_{max}$ increases for samples with higher NEC, reaching a maximum for sample C using flash powder of 2950 kPa/ms. Pyrotechnic articles use the explosive compositions in a confined manner inside the container tube, which means that the explosion parameters are significantly increased compared to an explosion of dispersed dust cloud in the air, as can be seen with values analysed in the literature for dust explosions of aluminium nanopowders and flash compositions, which are significantly lower (Bouillard, 2015; Wu et al., 2010). Therefore, this indicates a highly explosive and aggressive deflagration behaviour for the flash banger. On the other hand, the addition of inert materials to highly flammable materials reduces the P_{max}, as does $(dP/dt)_{max}$ (Kuai et al., 2011), as confirmed by the results obtained.

Samples with inert are compared. The trend observed indicates that by adding a certain inert composition to the flash powder, the explosion pressure generated decreases. It can be seen that this reduction is greater in sample B than in sample A or C. Comparing the values obtained for sodium bicarbonate and recycled glass, it is again observed that bicarbonate is more effective and reduces the explosion pressure to a greater extent than recycled glass using the same concentration. This difference is even more accentuated in the C samples, where variations of approximately 75 kPa between compositions 20G and 20B are seen when comparing mean values. Predictably, the higher the concentration of inert, the lower the pressure obtained should be. This is confirmed by the results obtained. Compositions using 20 % inert in their concentration generate a lower pressure than those using 10 % inert, as can be seen for sodium bicarbonate compositions for samples A (132.7 and 234.7 kPa for 20B and 257.1 and 272.1 kPa for 10B). This is due to the fact that by using more inert, the amount of flash powder is reduced. Moreover, the addition of inert powder reduces the ignition sensitivity of the composition (Amez et al., 2023) and, according to (Dai et al., 2020), the explosion pressure of the mixture decreases as the concentration of inert dust increases.

When comparing the reductions obtained in sound pressure level and explosion pressure for the samples using inert, specifically those using a 20 % concentration of sodium bicarbonate, it is observed that a greater sound reduction (close to 50 %) than explosion pressure reduction (between 23 % and 43 % depending on the sample) is achieved. The reduction in explosion pressure due to the addition of inert materials to the flash powder could be compensated for by adding a higher charge to the banger. Future studies analysing other inert compounds should be carried out in order to confirm these trends. If it were possible to achieve similar explosion pressures in this way, such compositions could be used as alternatives to reduce emissions and noise.

In order to establish a relationship between Net Explosive Content (NEC) and explosion pressure, due to the other influencing factors, further tests must be performed analysing different container tube designs, waste paper and composition percentages. The same applies to nitrocellulose. In order to be able to use this type of composition as a substitute for flash powder, a higher energy release during combustion is required for correct functioning. Therefore, further tests must be performed analysing partial substitution of flash powder by nitrocellulose to conserve metallic fuels or with a higher nitrogen content.

4. Conclusions

Flash powder is a widely used compound due to its explosive characteristics. It is one of the main pyrotechnic mixtures, mainly used in bangers and pyrotechnic shells, and therefore, one of those responsible for the social difficulties to which this sector is currently exposed. Problems such as the disturbances in residential and urban areas caused by the noise levels or the emissions released into the atmosphere can be reduced if sustainable alternatives to this type of composition are studied.

Nitrocellulose ($[C_6H_7(NO_2)_3O_5]n$) or the addition of inert compounds such as sodium bicarbonate ($NaHCO_3$) and recycled glass, are compositions which could be possible alternatives to this type of explosive composition. Comparisons in the gas analyser show that these compositions studied significantly reduce CO_2 emissions, the main greenhouse gas contributing to climate change. Although nitrocellulose is an organic compound with a high carbon content, the lower combustion efficiency and temperature of its reaction in confined environments may result in higher CO emissions and thus reduced CO_2 emissions compared to flash powder. The latter, despite not containing carbon in its formulation, can lead to higher CO_2 emissions and lower CO emissions due to almost complete oxidation and high temperature combustion and very high energy release, which favours the oxidation of trace carbonaceous pollutants present in the experimental environment. Moreover, the addition of inert compounds allows a reduction in carbon monoxide emissions. This gas is not directly related to the greenhouse effect but contributes to the formation of other gases that are connected to it. In addition, these compounds prevent the release of perchlorate derivatives and metalliferous particles, two of the most harmful pollutants in fireworks. Other hazardous compounds such as NO_x were not analysed in this study and are suggested for future research.

However, nitrocellulose does not achieve a correct functioning of the banger, since it does not release enough energy to achieve the opening of the container tube. This fact makes its implementation in pyrotechnic shells impossible, since the opening of the shell would not be achieved and, thus, the desired visual effects would not be obtained. Therefore, the results obtained show that nitrocellulose is not a viable substitute under the conditions analysed. In order to reach higher temperatures and higher explosion pressure, partial substitution of flash powder by nitrocellulose can be a solution, due to the presence of metallic fuels in the composition. But also, the explosiveness of nitrocellulose is directly related to its nitrogen content, so increasing this from the 12.6 % that is used in the compositions used in pyrotechnics, it may be possible to achieve the desired performance.

On the other hand, the addition of inerts is a viable solution to reduce emissions and sound pressure levels. According to the results obtained, sodium bicarbonate is more effective and reduces sound pressure levels by about 50 % when using a 20 % concentration of sodium bicarbonate. Although the addition of inerts also reduces the explosion pressure generated, a greater decrease in sound than in pressure is observed. This makes its use in pyrotechnic articles viable, since by increasing the article's total charge, the same explosion pressure would be obtained and, therefore, the correct opening of the shell, reducing in turn the sound pressure level and emissions. These findings demonstrate that the strategic use of inert compounds can significantly reduce both gaseous emissions and acoustic impact without compromising the functional explosion pressure.

Although more tests are required to establish a Net Explosive Content (NEC) - Explosion pressure relationship, due to the influence of other factors such as design, material or percentages of each composition, and the evaluation of other inert compounds, it can be concluded that the addition of inerts to flash powder is a real alternative that would reduce its emissions and sound pressure level without compromising pyrotechnic performance integrity pyrotechnic performance integrity, which is an important contribution toward more sustainable pyrotechnics.

CRediT authorship contribution statement

David León: Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Isabel Amez:** Validation, Investigation. **Roberto Paredes:** Formal analysis, Conceptualization. **Dimitrios Pantelakis:** Visualization, Data curation. **Blanca Castells:** Writing – review & editing, Supervision, Resources.

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

Data will be made available on request.

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