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Characterization of the explosiveness of wood dust

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ABSTRACT

Factors that influence the explosiveness of wood dust, like particle size distribution, moisture content and microscopic structure, have been characterised. Sawdust flammability has been tested in a Hartmann tube. The Minimum Explosive Concentration and Minimum Ignition Temperature of dust clouds and layers have also been measured. Dust granulometry linked to the regularity of its structure and moisture are the essential parameters to generate or not an explosive atmosphere. Smaller particle size dust with a lower moisture content is much more likely to create an ignition and/or explosion risk. The samples have been classified into two groups, those collected from cutting processes and those found in the ventilation ducts or deposited in the facilities. The most dangerous samples are those from Group 2. In some cases, dust samples up to 35 % moisture or with particle size greater than 500 µm at maximum dryness are able to produce an explosion.

1. Introduction

Wood has always had a great importance in human life because of being a renewable material and very useful due to its different chemical, biological, physical and mechanical properties (Kminiak et al., 2020).

In its transformation from nature to its final use, it undergoes a large number of processes that it is necessary to know about in order to be aware of the possible dangers they may involve. Mechanical work such as wood sanding is an essential part of product manufacturing and during this process a large amount of dust is generated and deposited on floors, walls and surfaces in the working facilities (Pędzik et al., 2021).

According to the U.S. National Fire Protection Association (NFPA), a dust is defined as a finely divided solid with a diameter of less than 420 µm (0.017 in.). A dust will pass through a US No. 40 standard sieve (NFPA 664, 2020).

Smaller particles are more dangerous than coarse ones because of the larger total surface area and also smaller particles can be lifted into the air more quickly (Dobashi, 2009). This poses a health risk to workers, especially when the dust has a particle size of less than 100 µm, which can remain suspended in the air and be inhaled by workers causing diseases such as pneumoconiosis, asthma, chronic bronchitis and nasal cancer and also risks in the workplace related to increased fire or explosion hazards (Očkajová et al., 2020; Pałubicki et al., 2020; Yuan et al., 2015).

A combustible dust is defined as a finely divided combustible particulate solid that presents a flash fire or explosion hazard when suspended in air or the process specific oxidizing medium over a range of concentrations (NFPA 654, 2020).

As mentioned by Worsfold et al. (2012), three different types of dust which do not necessarily follow this definition and which may therefore be considered "nontraditional" dusts. The first such "nontraditional" dust type is nanomaterials, which are particulate matter with dimensions in the nanorange, much smaller than common dusts. The second "nontraditional" dust type to be explored is flocculent materials, which are nonspherical and instead have a more fibrous appearance. The third "nontraditional" dust type is hybrid mixtures, which can be any dust that also has an admixed gas or is wetted with an organic solvent. These three categories of dust are less frequently the topic of dust explosion research, and so their explosibility behaviours are less well-documented.

Dust explosions are a frequent and continuous risk in industries (Eckhoff, 2005). Not only wood, but also other biomass materials can explode when they form a cloud in the air with the appropriate concentration of dust and this dust is subjected to contact with an energy

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source (Ravindran et al., 2022; Mallick et al., 2018). Explosions and fires coming from combustible materials are a known hazard and can have devastating and irreversible effects (Berard et al., 2021). Different types of industrial plants can generate dust in their facilities during their manufacturing processes that can lead to an explosion and to the catastrophic loss of lives (Cashdollar, 2000).

In 2014, an accident in Poland led to the collapse of an industrial building due to an explosion of wood dust. The explosion was caused by the self-ignition of a wood dust mixture in a poorly ventilated machine. In addition, the first explosion raised the accumulated dust into the air causing a secondary explosion. A large number of workers and several firefighters were seriously injured (Krentowski, 2015).

In 2015, at a wood mill in Bosley, United Kingdom, where wood was being processed into a fine powder used to make laminate flooring, an explosion occurred, as a result, the factory was destroyed. Four workers died and more than thirty were injured (Amyotte, 2014).

In Spain we can also find some accidents like these, in 2016 there was an explosion and subsequent fire in the parquet factory of the company Wood Manners in Torrelavega (Cantabria). The explosion occurred in a silo, where three workers were located, one died and another suffered minor injuries and burns (Díaz, 2016).

More recently, in 2020, a fire broke out at a sawmill in Cap-Pelé, New Brunswick (Canada), completely destroying the facility and causing more than $2 million in property damage (Al-Hakim, 2020).

Organic dusts other than wood are also capable of causing serious explosions (Štroch, 2016; Hutcherson et al., 2015). In South Korea, in 2017, an explosion occurred inside a polypropylene silo in Yeosu Industrial Complex, causing a big fire inside the silo (Pak et al., 2019).

As reported by Cloney (2021) in his Mid-year Combustible dust incident report, from the global incident data, food and wood products made up over 60 % of the fires and explosions recorded. These materials also resulted in 61 % of the injuries and 62 % of the fatalities. Wood has caused in 2021, 12 fires, 7 explosions, 9 injuries and one death. As shown in the historical data, wood processing, wood products, agricultural activity and food production make up a large portion of the overall fire and explosion incidents. Since 2017 wood and wood products have ranged from 21 % to 28 % of the incidents, while agricultural activity and food production has ranged from 33 % to 50 %.

Portarapillo et al. (2021) state that dust explosion accidents in 2019 revealed a significant percentage related to the wood and wood products industry, about 31 % in the US, and storage silos are significantly impacted by dust explosion, among other equipment, with a total of 13 %.

Several factors, such as dust concentration, its composition and moisture content, particle size and shape or type of dust, influence the sensitivity to ignition and flame spread in the dust cloud (Eckhof, 2016).

In this study, the effect of different parameters on the hazardousness of wood dust will be analysed. Particle size distribution or granulometry of the dust is one of the most important factors (Vandličková et al., 2020). It has been studied the characteristics of wood dust explosions in the Hartmann tube and found that particle size and concentration of the wood dust affect the explosion (Pang et al., 2020; Khudhur et al., 2021).

Another parameter to be taken into account is the particle shape. Dust particles coming from biomass materials such as wood cannot always be considered spherical, they can be fibrous, needle-shaped or any other shape. So, wood can be considered as a flocculent material, materials that are nonspherical and have a fibrous (fluffy) shape (Worsfold et al., 2012; Amyotte et al., 2011). Flocculent fibers cannot be well characterized in terms of diameter but rather are better described in terms of a length-to-diameter ratio (NFPA 68, 2007). This variety, can make it difficult when sieving dust samples, because if the particles under study has one of its dimensions larger than the sieve holes size and the other two dimensions are smaller, depending on how it is deposited on the sieve, the particle will pass through the hole or not.

Moisture content of the dust is also an important factor, as it changes depending on the environmental conditions and aiŕs moisture, so it influences the explosiveness (Pérez-Peña et al., 2011; Dudarski et al., 2015). The risk of explosion decreases as the moisture content increases, the presence of water in the dust can reduce the explosion force and sensitivity to ignition of the dust cloud and it also causes agglomeration, which makes it harder to have a second explosion as it is more difficult to put the dust into suspension (Chang et al., 2022).

In addition to testing how the different variables affect the explosivity, tests will also be carried out to determine different parameters to better understand the characteristics of the dust samples. Thus, the Minimum Ignition Temperatures of layer (MIT_{layer}) and dust cloud (MIT_{cloud}) will be measured, which are the lowest temperatures, either when the dust is deposited as a thin layer or dispersed into the air and in contact with a hot surface or a furnace, at which the sample is capable of producing sparks, flame or explosion (Danzi et al., 2015; Liu et al., 2019). The determination of the Minimum Explosive Concentration is also useful in the characterisation of the dust samples (Abelha et al., 2016; Saeed et al., 2017; Pietraccini et al., 2021).

With all these data, the risk assessment of wood dust and the prevention of the formation of explosive atmospheres will be possible.

The aim of this study is to determine when a wood dust sample is likely to cause an explosion by characterising the factors influencing that explosion.

2. Material and methods

In order to carry out the different tests, wood dust samples of two types of pine: *Pinus radiata* and *Pinus sylvestris L.*; two types of oak wood: *Quercus petraea*, *Quercus frainetto*; a mixture of pine and oak, as well as medium density fibreboard (MDF) were collected throughout the primary wood transformation process in different sawmills and wood industries.

Samples have been characterised by moisture content and particle size, before explosivity tests, determination of Minimum Ignition Temperature of dust cloud and layer, Minimum Explosive Concentration and Scanning Electron Microscopy.

2.1. Moisture content

The moisture content is determined using the weighing difference method as described in UNE 13183–1 (EN, 13183–1, 2002), using the Ohaus Corporation MB90 Moisture Analyser.

2.2. Particle size determination

Once the moisture content of the sample collected is known, it is dried for 24 h in an oven at a constant temperature of 40 °C to ensure that all water has been removed before particle size distribution determination by sieving is carried out.

The initial samples are sieved using 200 mm diameter stainless steel sieves of FILTRA brand. The holes of the sieves have different sizes of 32, 63, 125, 250, 320, 400, 500, 630 and 1000 μm so it is possible to obtain different portions based on particles sizes, and all of them will be subsequently tested. In addition, the average weight value can be also determined as the value where one half of the particles have a larger particle size and the other half have a smaller particle size. To determine this value, the sieve residue is weighed on each of the sieves and a distribution curve is plotted to indicate the median value of the dust analysed (Database Combustion and explosion characteristics of dusts, 2022).

2.3. Minimum Explosive Concentration (MEC)

A modified Hartmann tube with a hot wire as ignition source is used to test whether a dust is explosive or not. This concentration is commonly used with dust samples and it is the smallest amount of sample that can cause an explosion. A method based on UNE 22333–90

(AENOR. UNE EN 22333–90, 1990) and 22335–92 standards is used to determine the MEC (AENOR. UNE EN 22335–92, 1992).

2.4. Explosivity as a function of moisture and particle size

This test is also carried out in the modified Hartmann tube where all the different samples are tested using different particle size distribution portions (separated and classified by sieving) and with different moisture content.

The working procedure is based on UNE 22336 (AENOR. UNE 22336, 1996) standard, so each sample is tested ten consecutive times, observing whether ignition (generation of flame) or explosion occurs in any of the repetitions. The process is repeated by increasing the moisture of the samples or the portions in each case until the time when no explosion or ignition occurs.

Pang et al. (2020) studied the effects of particle size and concentration on the flame propagation characteristics of poplar dust deflagration by Hartmann tube. Flame propagations in wood dust explosions were divided into three stages including ignition, vertical propagation, and free diffusion. Flame propagations for 0–50 and 50–96 μm particles were found to be dominated by homogeneous combustion, while flame propagation for 96–180 μm particles was controlled by heterogeneous combustion.

2.5. Minimum Ignition Temperature of dust cloud (MIT_{cloud})

To measure the MIT_{cloud} the MIT-3 equipment of Anko Trading Ltd. is used. That equipment allows the characterisation of wood dust by determining the lowest temperature at which a sample dispersed into the air forming a cloud can generate a flame. Test procedure is based on the one described ISO 80079–20–2:2016 standard (ISO/IEC 80079–20–2, 2016), although there are also other slightly different standards on which this process can be based too, such as the American standard ASTM E1491–06 (ASTM E1491–06, 2019).

2.6. Minimum Ignition Temperature of dust layer (MIT_{layer})

The equipment used is the LIT-3 from Anko Trading Ltd., formed by a hot plate where the dust layer is deposited measuring the temperature as it increases until a flame or a spark is generated. The working procedure is based on a modification of the test procedure described in the ISO 80079–20–2:2016 standard (ISO/IEC 80079–20–2, 2016), although there are also other slightly different standards on which to base this process, such as the American standard (ASTM E2021–15, 2017).

This test allows the determination of the lowest temperature at which a 5 mm layer of the sample can make the dust glow, generate sparks or flame.

2.7. Scanning Electron Microscopy (SEM)

This technique is used to determine the shape and structure of the particles, using the JEOL JSM-6460LV Scanning Electron Microscope that takes high resolution images so it is possible to observe the morphology for samples before sieving and the different fractions, so the variation in particle shape as the size decreases can be observed.

In addition, particles from samples before and after the explosion will be compared, so that it will be possible to see how the structure and shape of the particles change.

3. Results and discussion

The explosivity tests have been carried out using the modified Hartmann tube with a hot wire as ignition source that simulates the heat of a surface or any element of a work equipment at high temperature that could be in the area where dust is generated.

In the tests, two reference standards will be used to compare the dangerousness of the rest of the samples with them. Lycopodium and Anthraquinone are usually used as calibration standards for the determination of minimum ignition energies (Verband Deutscher Elektrotechniker, 2013) with high voltage spark generation equipments. Both have been purchased commercially from Sigma-Aldrich with a very small average particle size, below 20 μm for Lycopodium and below 90 μm for Anthraquinone.

Table 1 shows the results obtained in the tests carried out with both products, obtaining the values corresponding to the maximum explosion moisture, the highest moisture percentage that a sample could have while it generates an explosion, and the maximum ignition moisture, the highest percentage of water content while a flame continues to be generated. In both cases, the criteria are based on the observation of flame greater than 10 cm for maximum ignition moisture or explosion for maximum explosion moisture. The MEC and the MIT_{cloud} and MIT_{layer} values have also been measured.

The same tests have been carried out with the different wood samples collected, coming from several species throughout the entire production process (sanding, suction, splitting, etc.) in order to compare the characteristics of the different wood samples. Table 2 shows the results obtained for the different samples before sieving, all the values correspond to the most dangerous sample of each of the types of wood tested.

In Table 2 it is possible to observe that there is a relationship between the maximum explosion and ignition moisture values and the particle size. The lower the average particle size, the higher the moisture percentages up to which flame or explosion is still generated, so, the higher the value of these water content must be for the sample not to explode or generate flame, the greater the danger they pose.

Same thing happens for MEC, MIT_{cloud} and MIT_{layer}, when the particle size is smaller, the dust can generate a flame with lower dust/air concentrations and at lower temperatures. This behaviour pattern is repeated for all the wood species studied, the higher the moisture and the larger the particle size, the lower the danger of ignition or explosion.

Table 1
Parameters of the standards: MEC, MIT_{cloud}, MIT_{layer}, maximum explosion moisture and maximum ignition moisture.

Parameters	Lycopodium			Anthraquinone		
	Portion (μm)		Before sieving	Portion (μm)		Before sieving
	< 32	32–63		< 32	32–63	
MEC (g/m^3)	19.50	31.19	27.29 /22 (Khudhur et al., 2021)	–	19.50	19.50
MIT_{cloud} (°C)	460 /390–440 (Gestis-dust-ex.)	460	460	680	680/ 650 (Gestis-dust-ex.)	660
MIT_{layer} (°C)	289–290 (Gestis-dust-ex.)	300	290	–	–	–
Maximum explosion moisture (%)	–	29.00	20.76	–	19.50	19.00
Maximum ignition moisture (%)	–	30.27	23.30	–	19.50	19.60

a: BAM oven for lycopodium < 32 μm sample. Database Combustion and explosion characteristics of dusts, 2022.
b: G-G oven for anthraquinone 32–63 μm sample. Database Combustion and explosion characteristics of dusts, 2022.

Table 2
Parameters of wood samples before sieving: MEC, MIT_{cloud}, MIT_{layer}, maximum explosion moisture and maximum ignition moisture.

Wood type	Average particle size (μm)	Moisture at the time of collection (%)	Maximum explosion moisture (%)	Maximum ignition moisture (%)	MEC (g/m^3)	MIT_{cloud} (°C)	MIT_{layer} (°C)
MDF	70.40	7.39	30.69	35.40	39.00	460	320
Quercus petraea	144.08	9.95	28.44	31.80	58.49	460	320
Pinus radiata	265.15	10.34	28.50	29.99	77.98	500	360
Pinus sylvestris L.	288.61	10.61	26.86	27.89	77.98	540	340
Mixture of pine and oak	378.60	9.64	4.13	5.36	194.96	540	340

a: For MIT cloud determinations the working conditions are 0,5 g and 0,5 bar.

3.1. Explosivity as a function of moisture and particle size

In order to carry out these tests, each of the samples has been tested, using an approximate value of 585 g/m^3, as the test concentration for each of the portions that have been classified by sieving. This concentration is established as a reference after several previous tests in which the initial amount of wood introduced into the Hartmann tube was increased from very low concentrations, around 35 g/m^3, in which the sample amount was so small that it barely managed to contact the ignition source. This amount was progressively increased to concentrations above 1000 g/m^3, which were sometimes excessive and could not be raised by blowing air. So, an intermediate concentration was chosen.

Fig. 1 shows the water content up to which the two standards samples and the samples before sieving can lead to an explosion or flame generation, moisture values above those will ensure that not explosion or ignition occurs. The criteria are based on the visual observation of a flame greater than 10 cm or explosion in a sample with the concentration specified in the previous paragraph and the water content indicated for each case in the figure according to ISO 80079–20–2:2016 standard (ISO/IEC 80079–20–2, 2016).

The mixture of pine and oak and pine shows the most different results, a fact that is related to its average particle size which is much bigger than the rest of the wood samples or standards. This sample was collected directly from the cut logs of both pine and oak. The rest of the samples were collected after further processing, either in the suction ducts or as dust deposited at the facilities.

Based on the results obtained, the samples have been classified into two groups. Group 1 contains the wood dust samples that come directly from the cutting processes, the so-called "coarse" samples, in which the number of small particles (< 250 μm) is very low. Group 2 includes all the samples that have undergone a larger number of processes such as sanding, suction, etc. and whose average particle size is smaller.

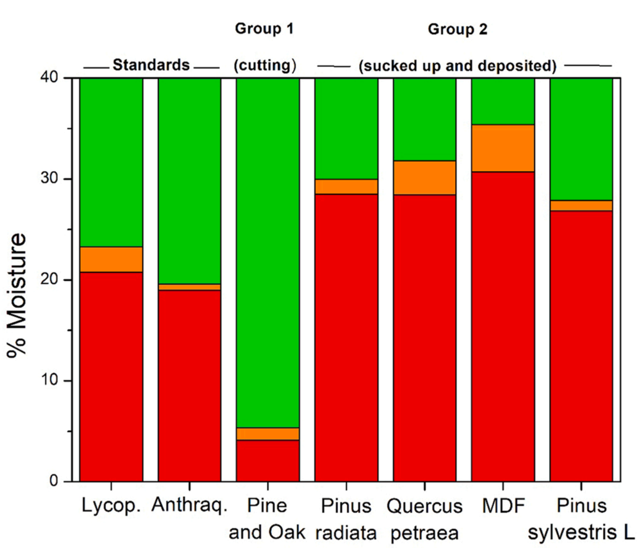

Fig. 1. The variation of the maximum explosive moisture for before sieving samples of Lycopodium (Lycop.), Anthraquinone (Anthraq.), a mixture of Pine and Oak, Pinus radiata, Quercus petraea, MDF and Pinus Silvestris L. Explosion Zone (red), Ignition Zone (orange) and Non-Explosion Zone (green) are shown. The tests have been carried out with a sample concentration of 584.90 g/m^3.

A classification similar to this one had been made previously by Marmo et al. (2019). They established that the “ambient dust” samples were found to be more explosible than the machinery dust samples so the sampling location has great importance for the actual evaluation of explosion hazards. The unit operations of the textile industry include vigorous mechanical operations that produce and deliver fines. In most cases, these fines are collected at the machines, but a certain amount is unavoidably distributed in the work environment and settles on surfaces where it forms layers. This is referred to as “ambient dust”.

Since textile industry has very different processes and machinery compared to wood industry, we have made some differences in our classification. In wood industry dust can proceed from machinery that generate a very small particle size, such as sanding, so its characteristics are more similar to ambient dust than to dust coming from other processes or machines.

Fig. 2 shows the maximum explosion and ignition moisture values for Group 1 (Fig. 2 A) and Group 2 (Fig. 2 B) as the average grain size increases. A relationship has been established between the water content, the particle size and the explosiveness of the samples. Experimentally, four zones have been distinguished: Explosion zone (red), Ignition or Flame (orange), Safety Margin (which has been calculated by setting 25 % above the Ignition Zone, in red dots) and Non-Explosion (green).

From Fig. 2 A it is inferred that Group 1 samples, coming directly from the cut, containing particle portions smaller than 125 μm are explosive (Red Zone) up to moistures around 30 % and portions with a particle size between 125 and 250 μm are explosive up to a moisture content of about 14 %. These samples are not so dangerous as their average particle size is above 250 μm when they are collected, and their moisture content is around 7 %, thus they would be in the green Non-Explosion Zone.

Group 2 includes the samples collected in the suction or extraction ducts and the dust that is deposited. Their behaviour has been depicted in Fig. 2 B. In this case the risk of ignition and/or explosion increases considerably. As shown in Table 2, the moisture conditions at the time of collection for this samples are around 10 %, placing these values in the red or Explosion Zone in Fig. 2 B for all samples with average particle sizes lower than 500 μm. When the particle size is below 63 μm, these dust samples can produce an explosion up to water contents around 40 % knowing that samples classified into this group have a high proportion of fines particles, smaller than 125 μm, something that makes Group 2 samples much more dangerous than Group 1 ones.

As the average particle size increases the percentage of moisture of the explosion zone decreases, but the samples from Group 2 remain hazardous even in the range of 500–630 μm, although the definition of dust usually only refers to solid particles smaller than 500 μm (García-Torrent, 2003). These samples in the 500–630 μm portion can produce an explosion at up to 7.9 % moisture and generate flames up to 9.2 % water content, values that are close to those registered when the samples were collected.

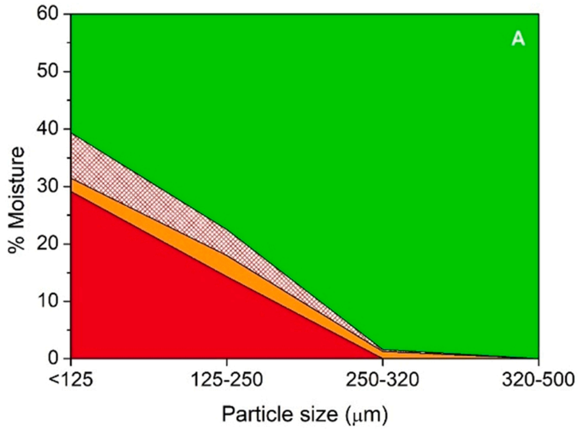

Fig. 2. Evolution of the hazard of the samples related to moisture and particle size. Explosion Zone (red), Ignition Zone (orange), Safety Margin Zone (red dots) and Non-Explosion Zone (green). A - Group 1, samples collected directly from cutting processes. B - Group 2, samples collected from suction ducts or dust deposited around machines in the facilities. The tests were carried out with a sample concentration of 584.90 g/m^3.

3.2. Minimum Ignition Temperature in dust cloud (MIT_{cloud})

Tests have been carried out on the not sieved samples as well as on the fractions, from the smallest particle size (32–63 μm) to 400–500 μm, so that we can make an idea of how particle size affects the minimum ignition temperature of a dust cloud. In all these tests, sample quantities of 1 g or less and pressures between 0.4 and 0.6 bar have been used.

The results obtained are shown in Fig. 3, where a relationship between particle size and MIT_{cloud} for the different species is observed.

It is observed that the temperatures are maintained without large variations below 500 °C when the samples have particle sizes up to 250 μm. In these fractions, there are no major differences for the different species, although MIT_{cloud} is slightly lower for samples containing oak.

This behaviour changes when analysing the sample portions with larger particle sizes. The minimum temperatures increase more rapidly and the species begin to differentiate between them, especially the samples of Quercus petraea and the mixture of pine and oak. These pair of samples presented the lowest MIT_{cloud} when the particle size is small but, from 250 μm onwards, they are clearly separated from the rest of the samples, presenting very high MIT_{cloud} values, which even exceed 700 °C.

3.3. Minimum Ignition Temperature in dust layer (MIT_{layer})

As well as it was done to determined MIT_{cloud} values, these tests have been carried out on both, not sieved samples and sieved fractions, so it is possible to observe the relationship between particle size and MIT_{layer}. In all tests, 5 mm thick layers were used.

The results obtained are shown in Fig. 4, the MIT_{layer} values are below 400 °C for every species and every fraction of them. In the case of the oak samples, the temperatures are slightly lower compared to rest of the samples, especially in the portions with smaller particle size, although the differences are not very marked, which is very similar to what happened with the MIT_{cloud}.

3.4. Scanning Electron Microscopy (SEM)

SEM images of different samples have been taken, both of the sieved samples whose average particles size is small and the bigger ones, and even of the samples after the explosion has happened. With all these images is possible to observe how the structure of the dust particles

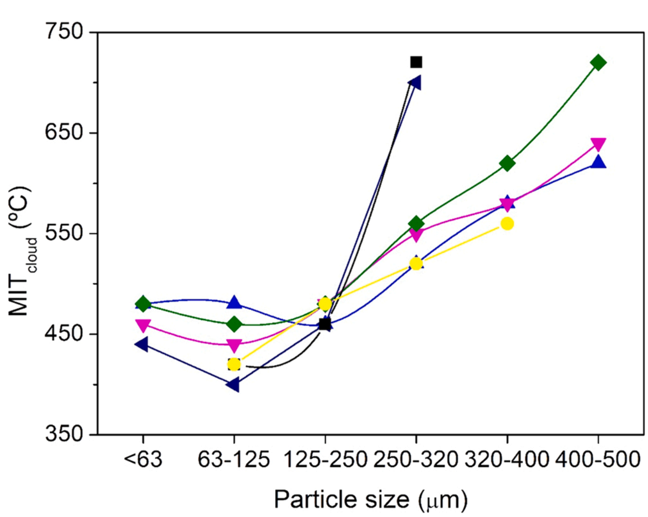

Fig. 3. MIT_{cloud} and particle size of samples sieved at maximum dryness. Pine and Oak (■), Pinus radiata (▲), MDF (▼), Pinus Silvestris L. (◆), Quercus petraea (◀) y Quercus frainetto (●).

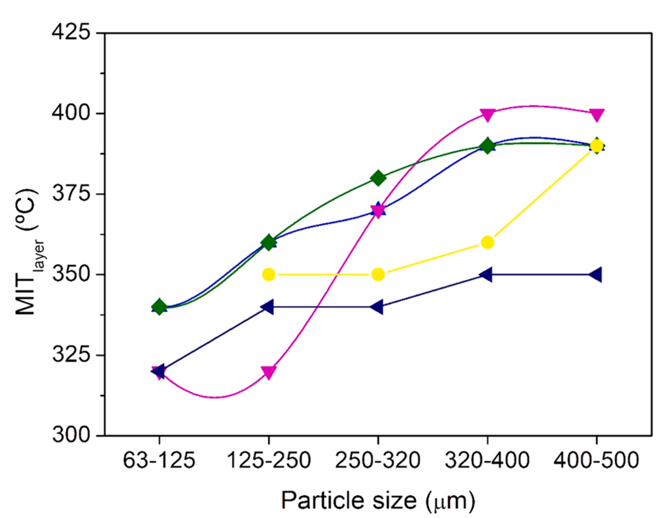

Fig. 4. MIT_{layer} and particle size of samples sieved at maximum dryness. Pine and Oak (■), Pinus radiata (▲), MDF (▼), Pinus Silvestris L. (◆), Quercus petraea (◀) y Quercus frainetto (●).

varies, and also to measure and verify that the size of the particles is indeed in the range of the granulometric fractions.

The different behaviour between Group 1 samples, from cutting processes, and Group 2 samples can be explained by the structural difference between them. Fig. 5 A shows that Group 1 particles maintain a defined structure even when their particles are smaller than 250 µm; this does not happen in the case of Group 2 samples (Fig. 5 B), that have undergone different processes and are much more structurally destroyed. Dust particles from samples coming from Group 2 no longer have the characteristic elongated channel network structure of the wood cells.

The changes in the structure of dust particles when they are small and destroyed make them have a higher surface to mass ratio, so that the area available for contact with the ignition source or for transmitting the flame from other particles is greater in relation to their mass than in the larger particles with a defined structure. This fact explains the greater danger in the generation of explosive atmospheres of samples with smaller particle sizes.

Differences in the shape and structure of the particles before and after the explosion have also been analysed as can be seen in Fig. 5C and D, which correspond to a mixture of pine and oak sample of an average particle size between 125 and 250 µm. Fig. 5C shows the structure of that sample before been exploded, with a defined structure, and Fig. 5D corresponds to the same sample once is exploded and some particles have been destroyed.

The explosion produces smaller particles, destroying their structure so after the explosion dust characteristics are more favourable for re-explosion, having now a lower moisture content and higher surface to mass ratio. This is why possible second explosions in industry are even more dangerous and destructive.

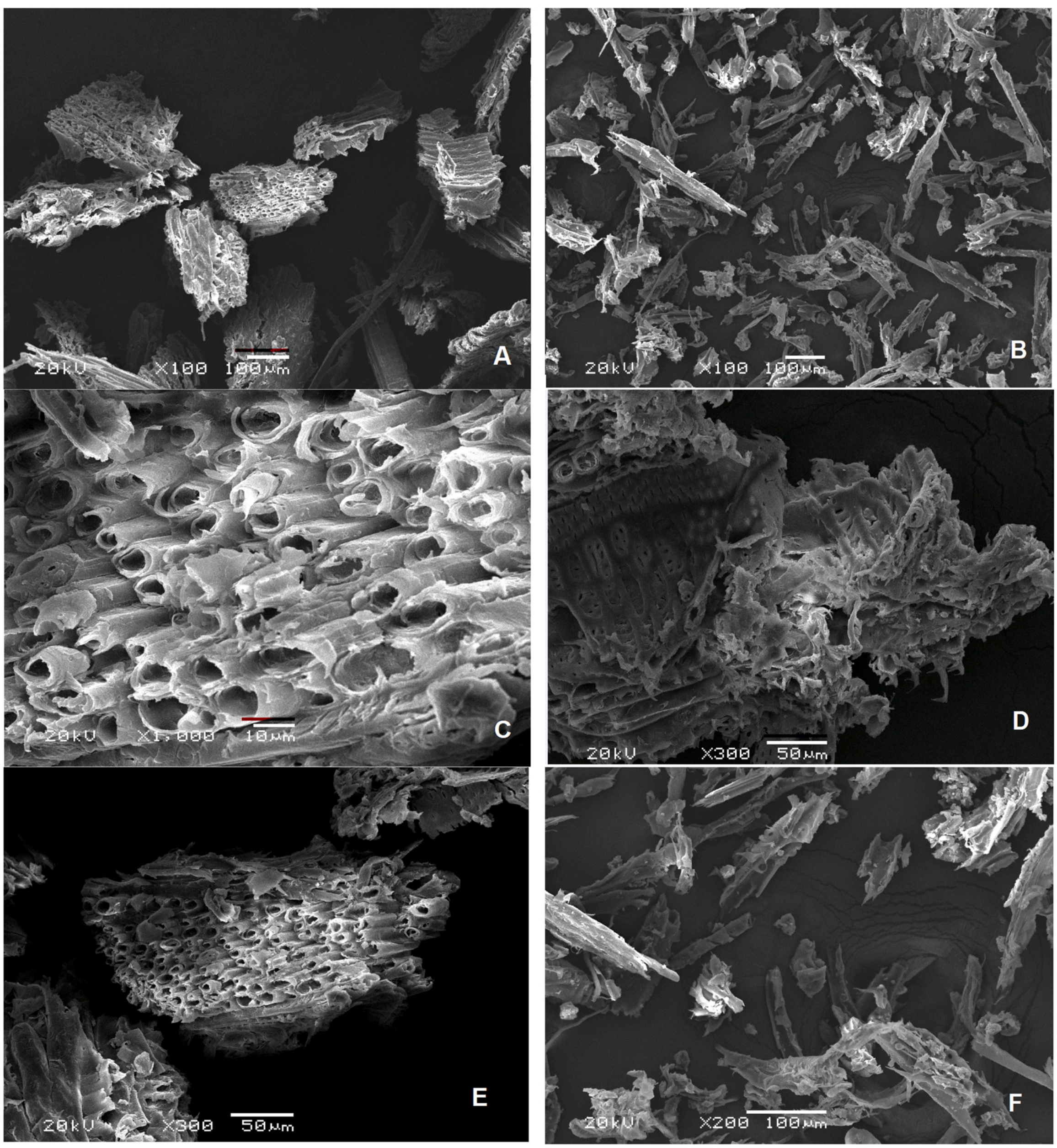

Fig. 5. Scanning Electron Microscopy (SEM) comparative photographs of samples, all of them from the 125–250 µm particle size range: A - Group 1 Pinus radiata sample (x100 magnification); B - Group 2 Pinus radiate sample (x100 magnification); C - mixture of pine and oak sample before the explosion (x1000 magnification); D - same sample after the explosion (x300 magnification); E - mixture of pine and oak from Group 1 (x300 magnification); F - Pinus radiata sample from Group 2 (x200 magnification).

Microscopy makes it possible to know how the internal structure of the particles is and to understand the shape differences between Group 1 and 2 samples. In Fig. 5E and F, where two samples that have same particle size (between 125 and 250 µm), are really different structurally, Fig. 5F, that corresponds to a Group 2 sample, presents a much more destroyed structure, which is key to understand the different behaviours shown in Fig. 2.

4. Conclusions

The granulometry, structure and moisture are decisive facts to generate or not an explosive atmosphere. Dust is much more likely to create an ignition and/or explosion hazard as its particle size is smaller and its moisture becomes lower.

Analysed samples have been classified into two groups depending of their origin and behaviour. Group 2 samples have smaller particle size and they are structurally destroyed, what make them much more dangerous. No relationship between the different species tested and their explosive behaviour has been observed.

Both the particle size distribution or granulometry linked to the regularity of its structure, as well as the moisture are the determining parameters when generating or not an explosive atmosphere. Dust that is more finely divided (smaller particle size) and with a lower degree of moisture is much more likely to create an ignition and/or explosion risk. In addition, dust particles that have already been involved in an explosion are capable of exploding again, making them even more dangerous as the explosion process further destroys their structure and increases their dryness.

In addition, dust fractions up to 630 µm can produce an explosion up to 7.9 % moisture content.

Finally, it is considered that, through the tests carried out, parameters such as moisture, particle size and shape have been identified that make it easier to assess the probability of the formation of an explosive atmosphere with the help of Fig. 2.

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CRediT authorship contribution statement

Alba Santamaría-Herrera: Investigation, Data curation, Writing – review & editing. **F. Javier Hoyuelos:** Project administration, Supervision, Funding acquisition, Writing – review & editing. **Carlos Casado-Marcos:** Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: F. Javier Hoyuelos reports financial support was provided by Junta de Castilla y León.

Data Availability

No data was used for the research described in the article.

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