Journal of Loss Prevention in the Process Industries 99 (2026) 105824

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Towards the valorization of spent coffee grounds: Experimental evaluation of flammability and explosion hazards

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ARTICLE INFO

Keywords:
Deflagration index
Dust explosion
Green processes
Minimum ignition energy
Minimum ignition temperature
Waste valorization

ABSTRACT

The global production of coffee is constantly increasing, and it is inevitably associated with the generation of a huge amount of waste, commonly discharged. Environmental awareness is leading towards the valorization of this material through the recovery of high-added value compounds. In recent times, industries are focusing their attention on the treatment of biomasses like spent coffee grounds, whose load, handling, and storage could introduce novel unforeseen hazardous scenarios. Indeed, hazards related to biomass dust still remain underestimated and partially unknown, leading to possible accidents like fires, explosions, and carbon monoxide emissions. This work deals with the investigation of the flammability and explosion properties of spent coffee grounds (SCG), monitoring the evolution of such properties as a function of the unit operations of the analyzed process, as a novelty in the field. SCG after treatments showed slightly higher flammability and explosiveness results, reporting minimum ignition temperatures for dust clouds between 420 °C and 440 °C and maximum explosion pressure and deflagration index of 7.5 bar and 35.1 bar m/s, respectively. Indeed, their chemical composition comprised higher volatiles, cellulose, and lignin contents, leading to an enhanced sensitivity to ignition, although not further compromising SCG safe handling and storage. All tested samples did not present significant hazards when exposed to an electrical discharge of up to 3000 mJ. In view of practical application for plant design, experimental findings allowed allocating them in the explosion class *St1*, corresponding to low explosion hazard.

1. Introduction

Coffee is one of the most widespread beverages in the world and its commercial growth has covered the last 150 years (Murthy and Madhava Naidu, 2012). Its global production has increased about 60 % since 1990s (International Coffee Organization, 2020). The International Coffee Organization estimated a global coffee consumption of 178.0 million bags for the year 2023/2024, with a growth rate equal to 5.8 % with respect to the previous year (International Coffee Organization, 2023). Coffee plants are evergreen shrubs or small trees, native of the Ethiopian mountains and they belong to the *Rubiaceae* family, which comprises about 400 genera and 5000 species. Its sub-genus Coffea includes over 80 species. Among them, *C. arabica* and *C. canephora* are the most widely popular on the market, native of Ethiopia and Central Africa, respectively (Murthy and Madhava Naidu, 2012; Patui et al., 2014). Depending on the processing method, in each production step, coffee industry generates different kinds of solid residues, such as pulp husk, silver skin, and spent coffee grounds (SCG). They represent about 50 % of the initial coffee feedstock mass. In particular, SCG, which is produced in thousand tons at public and domestic levels, could be a cheap source of high-added value compounds like caffeine and polyphenols, lipids, polysaccharides, hemicellulose, lignin, and proteins (Bravo et al., 2013; Ganesh Saratale et al., 2021; Mendes et al., 2019; Murthy and Madhava Naidu, 2012; Pujol et al., 2013). Improper disposal can increase treatment and landfill management expenses (Schmidt Rivera et al., 2020). Indeed, coffee waste is commonly disposed in landfills or incinerated, representing a source of pollution due to recalcitrant components like caffeine, tannins, and polyphenols (Mata et al., 2018). Their content is toxic for several plants (Cervera-Mata et al., 2018), due to their ability to inhibit plant growth (Yamane et al., 2014). Fernandes et al. (2017), reports that coffee waste may induce mutagenicity in different strains when disposed in landfills, causing DNA damage and

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https://doi.org/10.1016/j.jlp.2025.105824
Received 10 July 2025; Received in revised form 19 September 2025; Accepted 22 October 2025
Available online 22 October 2025
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Table 1
Examples of accidents in the agri-food industry sector.

Accident	Date	Where	Dust type	Industry type	Cause	Damage	Ref.
Grain silo explosion	20/08/1997	Blaye, France	Grain	Cargo handling	Mechanical shocks or friction around the fan on the central dust removal circuit. self-heating at the level of the dust storage tank.	11 deaths, 1 injury, major material damage.	ARIA
Fire in a dairy factory	14/04/1999	Leppersdorf, Germany	Powder milk	Manufacture of dairy products	Smoldering nests of dust deposits ignited spontaneously during the drying process shutdown/start-up, associated with the product change.	No injuries, major material damage.	ARIA
Release to water and ground of a molasses vessel	27/07/1999	–	Molasses	Manufacture of food products and beverages (Seveso Lower Tier)	Rupture of the molasses storage vessel due to corrosion. Inadequate maintenance and inspection of the non-chemical vessels.	No injuries, no material damage, minor water and land pollution.	eMars
Overheating of grape seeds in an oil mill	14/12/1999	Lezay, France	Grape seeds	Manufacture of oils and fats	Self-heating of the grape seeds contained in the storage cell.	No injuries, minor material damage.	ARIA
Asphyxiation of operators	15/02/2001	–	Food additive	Food additive production plant	Filter cakes, made of sulphurated organic material, generated and released hydrogen sulfide and methane, exceeding the H_2S concentration threshold.	2 deaths, no material damage.	eMars
Belt conveyor fire in a silo	09/10/2003	Creully Sur Seulles, France	Bran	Support activities for crop production	Maintenance work carried out the day before, involving the use of a grinder.	No injuries, no material damage.	ARIA
Fire in a sugar refinery-distillery	08/09/2004	Lillers, France	Sugar	Manufacturing of sugar	Sparks generated by the welding of galvanized bars ignited the dust in the area, fairly accessible and not sufficiently clean.	No injuries, minor material damage.	ARIA
Grain silo explosion	14/04/2005	Huesca, Spain	Grain	Manufacture of grain mill products	Lightning.	19 injuries, major material damage.	ARIA
Fire of a dust removal filter	25/05/2005	Beziers, France	Grape seeds	Manufacture of oils and fats	Water infiltration inside the safety membrane, causing the dust fermentation, with subsequent self-ignition.	No injuries, minor material damage.	ARIA
Dust explosion in a dryer	24/12/2007	Lillebonne, France	Corn	Manufacture of other organic basic chemicals	Spontaneous combustion of the residual wet spent grains inside the burner, which turned on due to a malfunctioning of the hopper scale, causing the non-activation of the safety devices.	2 injuries, minor material damage.	ARIA
Explosion and fire in a sugar factory	07/02/2008	Savannah, USA	Sugar	Manufacture of sugar	Overheating of a bearing in the conveyor steel belt, with subsequent explosion of accumulated sugar. Domino effects caused secondary explosions.	14 deaths, 36 injuries, major material damage.	ARIA, Chemical Safety Board
Wheat dust combustion in an underground technical gallery	02/02/2009	Corbeil-Essonnes, France	Grain	Manufacture of grain mill products	Overheating was caused by the binding of one of the 100 belt guiding rollers. The accumulation of dust exceeded the threshold value of 50 g/m^3 due to a process change in the grain cleaning, causing the fire. The sprinkler-based extinction system did not activate due to insufficient heat flux.	No injuries, minor material damage.	ARIA
Explosion in a corn starch cell in a silo	19/03/2009	Lestrem, France	Corn starch	Manufacture of starches and starch products	Electrostatic discharge between the stainless-steel ball of the manual level measurement device and the cell roof, causing an ignition of a suspended starch cloud.	No injuries, minor material damage.	ARIA
Fire in a dryer	16/10/2010	Chavanges, France	Grain	Wholesale of grain, unmanufactured tobacco, seeds and animal feeds	Dust particles had accumulated near the hot air inlet to the drying column, they overheated, causing a fire.	No injuries, minor material damage.	ARIA
Fire in a corn dryer	17/10/2012	Ecouflant, France	Corn	Wholesale of grain, unmanufactured tobacco, seeds and animal feeds	Overheating of corn dust, attached to one of the dryer accesses hatches due to a worn riveted plate.	No injuries, minor material damage.	ARIA
Corn dryer fire outbreak in a silo	07/12/2012	Belpech, France	Corn	Wholesale of grain, unmanufactured tobacco, seeds and animal feeds	Malfunction during the opening phase of the burner's air supply louvers, due to a failure of the jack, causing the burner to operate abnormally, with subsequent filter combustion.	No injuries, minor material damage.	ARIA
Fire in a silo storage bin	19/08/2013	Saint-Jean-Sur_Veyle, France	Sunflower meal	Manufacture of grain mill products	Self-heating of sunflower meal dust	No injuries, minor material damage.	ARIA

(*continued on next page*)

Table 1 (*continued*)

Accident	Date	Where	Dust type	Industry type	Cause	Damage	Ref.
Explosion in a flour silo	31/07/2013	Fossano, Italy	Flour	Grain milling and flour storage plant	High flour concentration in the air, due to a higher amount of flour than that admissible. Lack of suitable ventilation, monitoring, alarm, and protecting systems.	5 deadly injuries, major material damage.	Dors
Fire in a grain-silo storage bin	02/11/2013	Bassens, France	Sunflower seeds	Manufacture of oils and fats	Self-heating inside a hull processing hopper upstream the dust storage tank.	No injuries, minor material damage.	ARIA
Explosion in the handling facilities of a port silo	02/01/2014	Boucau, France	Grain	Warehousing and storage	Excessive dust accumulation inside the handling equipment and frictional heating of the accumulating particles, overcoming the lower flammability limit for corn.	1 injury, minor material damage.	ARIA
Explosion and fire in a corn dryer	19/11/2014	Beaune, France	Corn	Wholesale of grain, unmanufactured tobacco, seeds and animal feeds	Pre-storage of a batch of several tons of wet dust for a prolonged period, excessive emptying of the drying column and maintenance of the ventilation system, creating a high amount of suspended dust. Absence of a well-defined procedure for non-compliant batches.	1 injury, minor material damage.	ARIA
Fire in the flour drying system of a flour mill	29/02/2016	Strasbourg, France	Grain	Manufacture of grain mill products	Self-heating of residual flour still present during the equipment shutdown	No injuries, minor material damage.	ARIA
Molasses leak in a sugar factory's storage facility	18/03/2016	Baie-Mahault, France	Sugar	Warehousing and storage	Leak of molasses from a storage tank, subject to aging. Lack of maintenance.	No injuries, minor material damage, minor water and land pollution.	ARIA
Glucose leak at a confectionery factory	19/01/2018	Neuville-En-Ferrain, France	Glucose	Manufacture of cocoa, chocolate and sugar confectionery	Rupture of a pipe under the glucose silo.	No injuries, minor material damage, minor water pollution.	ARIA
Fire during dismantling work at a tea and coffee processing plant	04/07/2018	RouxMesnil-Bouteilles, France	Tea and Coffee	Processing tea and coffee	The use of a blowtorch to cut a metal generated sparks, which landed on the dry coffee grounds stored in a silo. The fire spread to the adjacent silo.	No injuries, minor material damage.	ARIA
Overheating of a storage bin in the silo of a malting plant	16/08/2018	Issoudun, France	Malt	Manufacturing of malt	Overheating of malt stocked in a silo for more than 48 h. The LEL concentration of malt was exceeded.	1 injury, minor material damage.	ARIA

presenting toxicity to aquatic organisms. The high organic load of SCG determines a huge demand of oxygen to be degraded (Silva et al., 1998), and the presence of phytotoxic and antibacterial polyphenols can represent a serious pollution risk for the soil and aqueous organisms (Mekki et al., 2007; Pettinato et al., 2023).

However, if properly recovered and treated, SCG can become a potential resource. Indeed, they show potentiality towards the extraction of valuable products like antioxidants and lipids, to be employed into the food and pharmaceutical sectors or for biodiesel and biopolymers productions or energy recovery. In this way, they could become a treasured economic resource, associated with a lowered environmental impact of production processes (Pettinato et al., 2019; Tun et al., 2020).

As a byproduct of the food industry, its handling could be perceived as safe and the potential hazards dangerously underestimated. In Italy, food and beverage sector has a great impact in the national economy, with a value of 193 billion Euro, and covering 15.6 % of the total turnover of the manufacturing sector (Ufficio Studi della Fondazione Metes, 2024). But, the food industrial sector is a branch characterized by high frequency of accidents and injuries, with workers exposed to health and process hazards, e.g., due to the use of sharp tools and working in close contact with moving mechanical parts of industrial machinery. In 2021, among the manufacturing sector divisions, the Food Industry stands out for the number of reports of injuries, with just over 11,000 cases, behind only Metal Products Manufacturing and Machinery Manufacturing. In addition, 33 workplace deaths (about one in six) were reported for the same time span (INAIL, 2023). Table 1 summarizes the main accidents pertinent to the food industry occurring over the time span 1997–2018. The primary risk factors in the sector investigated can be summarized as in the following:

1) **Hazardous substances.** Food safety is ensured by proper cleaning and maintenance of production lines, but during these phases workers can be exposed to hazardous substances, such as disinfectants, lubricants, or ammonia used in refrigeration systems.
2) **Biological agents.** Especially maintenance workers are exposed to *Salmonella, Hepatitis A,* bacteria, viruses, and parasites. Furthermore, workers of maintenance sector may come into contact with wastewater containing organic matter, acids, nitrates, oils, disinfectants, etc. Effective training for workers on biological risks is pivotal as the adoption of good hygiene practices, the use of protective equipment, health checks, and adequate vaccinations for operators.
3) **Dust.** The highest risk is represented by the flammability of dust (flour, wheat, corn, etc.), potentially leading to explosions. To prevent dust explosions, the control of all electrical equipment, repeated maintenance to avoid the layer of dust deposits greater than 5 mm are necessary operations. Dust can also cause damage to the respiratory system (such as bronchial asthma) and irritation.
4) **Equipment.** The number of accidents, especially cuts, abrasions, contact burns, etc., remains high and their consequences are sometimes disabling, with serious consequences for workers, both physically and psychosocially.
5) **Confined space.** Maintenance workers in the food industry use to work in enclosed spaces such as silos, barrels, presses, tanks, etc. Working in confined spaces is extremely dangerous due to the possibility of creating conditions of lack of oxygen, toxic fumes, sudden overflow of liquid or solid materials or powders, and conditions of

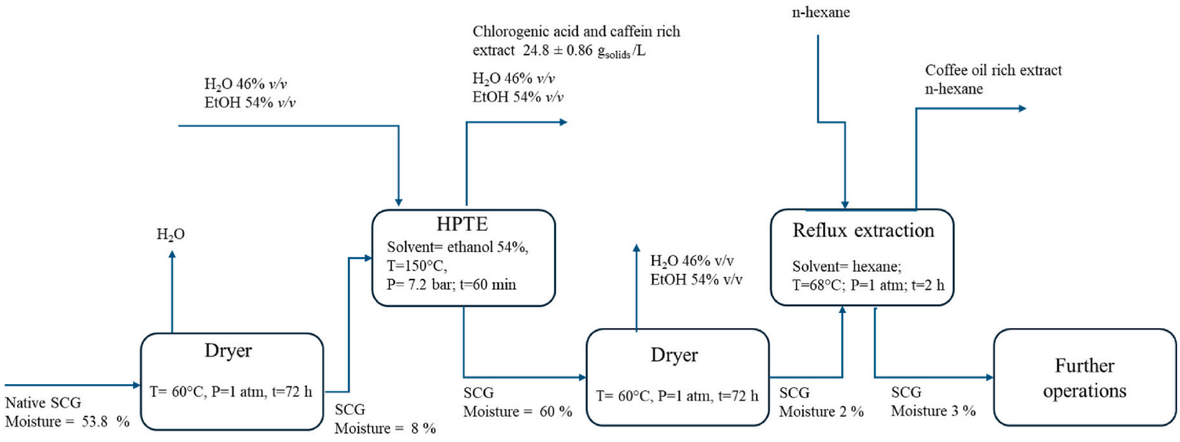

Fig. 1. Scheme of the extraction process treatments involving spent coffee grounds (SCG).

very high or very low temperatures. Poor visibility and difficulty in movement can aggravate the situation.

6) **Heavy work:** Ergonomic risks due to repetitive movements or manual handling of loads should not be overlooked. The ergonomic design of machines and equipment, the alternation of repetitive movements with other non-repetitive activities, can lighten the impact of this risk agent on the worker, as can the use of breaks and recovery times.
7) **Extreme temperatures:** Very hot and very cold environments are common in the agri-food sector. The associated risk can be reduced by limiting exposure time and providing adequate PPE, escape routes, and compensation environments for cooling and/or warming up (Salvati, 2015).

Among the unit operations, drying is particularly susceptible to fire and explosion hazards because it is a process in which external heat sources are applied. Data indicates that the accident rate is considerably higher in the food industry than in the chemical industry, and a remarkable number of explosions in the food sector are related to drying operations (Markowski and Mujumdar, 2006).

Indeed, the flammability and explosiveness properties of biomass dust remain partially unknown, resulting in potential accidents, including not only fires and explosions, but also carbon monoxide emissions (Castells et al., 2021; García Torrent et al., 2016). The concentration of dust clouds changes during the loading, storing, and discharging phases of a process and cannot be assumed to remain constant (Pahasup-Anan et al., 2022). Moreover, biomass is addressed as a "non-traditional" dust due to the non-spherical nature of its particles (Danzi et al., 2023), which present a fibrous and flocculating aspect (Pietraccini et al., 2021). Therefore, it is fundamental a deep comprehension on the interdependence among the explosion violence/ignition sensitivity, the physico-chemical properties of the solid matrix, such as particle size, moisture content, aging, composition, and shape, and the geometry of the equipment involved in the undesired event (Castells et al., 2021; Perelli et al., 2023; Santamaría-Herrera et al., 2023). In these regards, several authors have already characterized different types of agro-food biomasses, such as grape pomace (Danzi et al., 2021), lignocellulosic materials (Castells et al., 2021; Danzi et al., 2023), olive pomace (Pietraccini et al., 2021), and tea powder (Semawi et al., 2023), in terms of minimum ignition temperature (*MIT*), minimum ignition energy (*MIE*), maximum explosion pressure (P_{max}), maximum rate of pressure rise ($(dP/dt)_{max}$), dust deflagration index (K_{St}), and limiting oxygen concentration (*LOC*) (Kuracina et al., 2019; Perelli et al., 2023). Nevertheless, complete characterization studies of the flammability and explosiveness properties associated with dust biomasses are currently limited in literature. Only a few studies focused on the SCG explosion properties analysis, but they did not extensively treat this topic, limiting to a physico-chemical characterization of the matrix, the determination of thermal properties, *MIT*, and *MIE* (Bejenari et al., 2021; Todaka et al., 2016; Wachter et al., 2016). Furthermore, the current literature does not extend the analysis to biomasses alongside the different steps of the overall treatment process but is limited to the starting matrix itself. This introduces an experimental gap regarding the safety characterization of specific solid intermediates and products resulting from selected biomass processing.

As a peculiar novelty in the field, the flammability and explosion properties of SCG were thoroughly examined and characterized, both in the native and pre-treated form following its properties evolution alongside the processing. Investigated pre-treatments cover different extraction techniques, *ad-hoc* selected and optimized for the recovery of high-added value compounds, such as antioxidants and lipids. Upon refinement, the acquired knowledge on fire and explosion hazards can be used for a quantitative comparison of different conceptual design solutions that embed the process and preliminary risk analysis (Bassani et al., 2023).

2. Material and methods

2.1. Context of the study

In this study, SCG are proposed as raw material for a cascade of extraction operations aimed at determining its potential valorization as a source of bioactive compounds of interest for the industry (Pettinato et al., 2023). Fig. 1 depicts the section of the process treatments considered in this study and involving SCG.

SCG of *Coffee canephora* variety (COVIM S.p.A- Espresso Life) were collected from a common espresso vending-machine at the Department of Civil, Chemical and Environmental Engineering of the University of Genoa, Italy. After collection, SCG were dried in oven at 45 °C, until 4–6 % of the residual wet-based moisture was reached, and then stored in the dark and at room temperature. SCG were treated by two sequencing extractions with the aim of recovering both antioxidant and lipidic compounds. A high pressure and temperature extraction (HPTE) was employed to extract antioxidants like polyphenols and caffeine. To this aim, a 316 stainless steel stirred extractor (Parr Instruments Company, model 350M–4650 Series, Illinois, USA), reaching high temperatures (up to 350 °C) and high pressures (up to 200 bar), was exploited. HPTE was carried out at the following operating conditions, optimized in previous studies (Pettinato et al., 2019, 2020): 150 °C, 7 bar, extraction time of 1 h, 54 % (*v/v*) ethanol as extraction solvent, with a liquid-to-solid ratio equal to 10 mL/g. After the extraction, the solid residue was separated from the liquid extract by filtration (Ø 1.2 μm) and subsequently dried at 60 °C until 4–6 % of the residual wet-based moisture was reached. Subsequently, it was fed to a conventional

Table 2
Summary of the operating conditions tested for the conventional reflux extraction.

Sample Code	Solid type	Liquid-to-solid ratio (mL/g)	Extraction time (min)
A1	SCG	10	120
A2		6.7	120
A3		5	120
A4		5	90
A5		5	60
A6		5	40
A7		5	20
B1	SCG post HPTE	10	120
B2		6.7	120
B3		5	120
B4		5	90
B5		5	60
B6		5	40
B7		5	20

reflux extractor (RE), exploiting *n*-hexane as solvent. Different liquid-to-solid ratios and extraction times were investigated (Table 2). After the extraction, the solid residue was separated from the extracted oil by filtration (Ø 1.2 μm) and the two phases were stored in the dark and at room temperature for subsequent analyses and applications.

2.2. Biomass characterization

SCG samples were characterized in terms of total moisture, ashes, volatiles, particle size distribution, chemical composition, and thermal properties.

The total moisture content (% *wt*) was determined on wet basis by weighting about 5 g of the samples and analyzing them using the HS153 moisture analyzer (Mettler Toledo, Strašnice, Czech Republic).

The content of ashes and volatiles of the biomasses (% *wt*) was evaluated on dry samples, which were incinerated at 550 °C for 4 h.

The SCG particle size distribution was determined by the CILAS 1090 particle size analyzer (Cilas Particle Size, Orléans, France). Before the measurement, dry SCG samples were sieved to obtain a maximum particle diameter of 500 μm. Results were obtained in terms of cumulative function (*Q3*, %).

Changes in the chemical composition of SCG after its treatment through HPTE and RE were analyzed by means of attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR). FTIR spectra were recorded using Nicolet iS50 FTIR Spectrometer (Thermo-Fisher Scientific, Milan, Italy) with an attenuated total reflection (ATR) accessory coupled to a diamond crystal (Smart Orbit Diamond). Measurements were performed in the ATR mode within a spectral range of 4000- 400 cm^{-1}, at room temperature, and using a 4 cm^{-1} resolution and 32 scans. Spectra were investigated using the Omnic Software.

The biomasses thermal behavior was evaluated by thermogravimetric analysis (TGA). A thermobalance Next STA200 Thermal Analysis System (Hitachi High-Tech Analytical Science, Germany), with a weight sensitivity of 0.2 μg, was employed. Samples were heated from 30 °C to 1000 °C, with a heating rate of 10 °C/min, under a pure nitrogen atmosphere. Thermal degradation and stability behavior were determined by analyzing thermogravimetric (TG), differential thermogravimetric (DTG), and differential scanning calorimetric (DSC) curves.

Statistical analysis of the obtained results was carried out using Statistica software 12.0 (StatSoft, Tulsa, OK, USA). One-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) post-hoc multiple comparison test were performed to determine the statistically significant differences between the tested samples. Differences among the mean values were considered significant at $p < 0.05$.

2.3. Explosion properties of the SCG-derived biomasses

Explosivity properties for SCG and SCG-derived biomasses were evaluated in terms of *MIT*, *MIE*, P_{max}, $(dP/dt)_{max}$, K_{St}, and *LOC* (Limiting Oxygen Concentration). SCG, both in the native form and pre-treated by the extraction techniques described in section 2.1, were characterized. The analyses were performed on dry SCG samples (average moisture of 4.08 ± 0.29 % $wt_{wet\ based}$), stored in sealed containers, in the dark, at room temperature, and previously sieved to obtain a maximum particle diameter of 500 μm, since this size is considered ideal to evaluate powders explosion properties.

MIT was determined in accordance with the standard EN ISO/IEC 80079-20-2:2016 (2016). Experimental apparatus for *MIT* testing for dust clouds consisted in a furnace, equipped with a temperature controller, a dust container, a pressure regulator, and a mirror enabling the operator to monitor the dust explosion in the furnace bottom (Clasic, Řevnice, Czech Republic). Tests started at 500 °C by loading pre-weighted powder samples into the dust container. The sample mass and the test pressure were changed until the maximum explosion intensity was reached, after which the temperature was reduced in 20 °C intervals. If the ignition occurred within 5 s from the dust injection, the test was considered positive. For the highest temperature at which the ignition did not occur, tests were repeated three times. *MIT* for dust cloud was calculated with respect to the lowest ignition temperature, decreased of 20 °C, as a precautionary approach. *MIT* tests for dust layers were, instead, performed through a heating surface plate, equipped with a temperature controller (Clasic, Řevnice, Czech Republic). The layers height was 5 mm. Tests started at 400 °C, then decreased in intervals of 10 °C, until the layer ignition did not occur. For the highest temperature at which the ignition did not take place, tests were repeated three times. *MIT* for dust layers was calculated with respect to the lowest ignition temperature, decreased of 10 °C, as a precautionary approach.

The *MIE* determination was performed in accordance with the standards EN 13821:2002 (2002) (European Committee for Standardization, 2002), ASTM E:2019 (American Society for Testing and Materials, 2019b) and EN ISO/IEC 80079-20-2:2016 (2016) (International Organization for Standardization International Electrotechnical Commission, 2016a). To this aim, the apparatus MIE – D 1.2 (OZM Research s.r.o., Hrochův Týnec, Czech Republic), equipped with 1.2 L glass Hartmann tube, was employed. The dispersion occurred with an air pulse pressurized to 7 bar. The analyses were carried out on different amounts of dust, with a delay time of 120 ms and an inductance of 1 mH. The energy generated by the spark ranged between 1 and 1000 mJ.

Explosion parameters like P_{max}, $(dP/dt)_{max}$, K_{St}, and *LOC* were investigated by means of a 20 L explosion chamber (OZM Research s.r.o., Hrochův Týnec, Czech Republic) (Helegda et al., 2024). It consisted in a spherical double-walled stainless-steel vessel, equipped with two piezoelectric pressure sensors (Kistler, Prague, Czech Republic) and a glass opening, allowing to observe inside. Before each measurement, the chamber was partially evacuated to 0.4 bar. The dust injection was performed through an injection nozzle with retroreflection, according to the standard EN 14034-1+A1:2011 (2011) (UNI EN 14034-1:2011, 2011) with a delay time of 60 ms between the onset of dust dispersion and the activation of the dust/air ignition. For the highest energy at which the ignition did not occur, tests were performed in triplicate.

P_{max}, $(dP/dt)_{max}$, K_{St} were determined by a 20 L explosion chamber (OZM Research s.r.o., Hrochův Týnec, Czech Republic) over a wide concentrations range (starting from 60 g/m^3), according to the standards ASTM E1226:2019 (2019), EN 15967:2022 (2022) (European Committee for Standardization, 2022), and EN 14034–2:2006+A1:2011 (2006) (European Committee for Standardization, 2011a). Two 5 kJ chemical Sobbe's Ignitors (EBBOS ChZ Fr. Sobbe Gmbh, Dortmund, Germany) were used as ignition sources. The dust was injected through a retroreflective nozzle, with a 60 ms delay between dust dispersion and ignition.

Table 3
Moisture, ashes, and volatiles matter of SCG samples. Different letters within the single column correspond to significant statistical differences among data ($p < 0.05$, Tukey's HSD post-hoc multiple comparison test). HPTE=High Pressure and Temperature Extraction; RE = Reflux Extraction.

Sample	Moisture (% *wt* $_{wet\ based}$)	Ashes (% *wt* $_{dry\ based}$)	Volatile matter (% *wt* $_{dry\ based}$)
SCG	8.12 ± 0.36^{a}	1.77 ± 0.03^{a}	98.23 ± 0.03^{a}
SCG post HPTE	4.26 ± 0.24^{b}	1.73 ± 0.11^{a}	98.27 ± 0.11^{a}
SCG post RE (sample A5)	2.39 ± 0.16^{c}	1.49 ± 0.07^{b}	98.51 ± 0.07^{b}
SCG post HTPE + RE (sample B5)	3.52 ± 0.26^{d}	2.19 ± 0.01^{c}	97.81 ± 0.01^{c}

Table 4
SCG samples particles sizes corresponding to cumulative function values of 10 %, 50 %, and 90 % (D_{10}, D_{50}, and D_{90}). Different letters within the single column correspond to significant statistical differences among data ($p < 0.05$, Tukey's HSD post-hoc multiple comparison test). HPTE = High Pressure and Temperature Extraction; RE = Reflux Extraction.

Sample	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)
SCG	27.99 ± 2.69^{abc}	109.19 ± 0.83^{a}	254.5 ± 11.58^{a}
SCG post HPTE	35.59 ± 6.11^{c}	201.53 ± 2.85^{c}	396.86 ± 20.21^{b}
A1	21.44 ± 2.50^{a}	163.5 ± 11.85^{bc}	338.32 ± 24.04^{ab}
A2	24.03 ± 4.95^{ab}	161.48 ± 24.52^{bc}	339.42 ± 50.31^{ab}
A3	24.15 ± 0.96^{ab}	168.08 ± 10.00^{bc}	343.29 ± 30.16^{ab}
A4	24.69 ± 2.65^{ab}	170.65 ± 19.05^{bc}	364.22 ± 55.30^{b}
A5	24.22 ± 1.51^{ab}	181.28 ± 5.17^{bc}	375.19 ± 24.11^{b}
A6	24.77 ± 0.78^{ab}	141.09 ± 9.72^{ab}	298.84 ± 32.72^{ab}
A7	25.13 ± 1.75^{ab}	132.42 ± 13.69^{ab}	301.97 ± 44.97^{ab}
B1	20.89 ± 1.43^{a}	150.03 ± 12.99^{ab}	325.82 ± 21.88^{ab}
B2	23.70 ± 2.78^{ab}	157.52 ± 25.98^{abc}	327.53 ± 54.74^{ab}
B3	25.64 ± 5.55^{ab}	173.41 ± 11.59^{bc}	329.86 ± 36.63^{ab}
B4	20.12 ± 4.42^{a}	135.02 ± 10.90^{ab}	314.27 ± 35.18^{ab}
B5	32.21 ± 2.23^{bc}	141.87 ± 23.37^{ab}	396.45 ± 24.48^{b}
B6	23.40 ± 0.70^{ab}	138.48 ± 8.57^{ab}	311.85 ± 5.95^{ab}
B7	26.30 ± 2.67^{abc}	157.48 ± 37.10^{abc}	364.49 ± 50.10^{ab}

The measured explosion pressures were adjusted by Equations (1) and (2), according to ASTM E1226:2019 (American Society for Testing and Materials, 2019a), to make them comparable with those achievable by a 1 m^3 explosion chamber.

If the measured value of overpressure ($P_{max,\ measured}$) was lower than 5.5 bar:

$$P_{max} = \frac{5.5\ (P_{max,measured}\text{-}0.32)}{5.18} \tag{1}$$

If the measured value of overpressure ($P_{max,\ measured}$) was higher than 5.5 bar:

$$P_{max} = 0.775 \cdot P^{1.15}_{max,measured} \tag{2}$$

Regarding K_{St}, it was calculated through the cubic law equation, as in Equation (3).

$$K_{St} = \left(\frac{dP}{dt}\right)_{max} \cdot \quad V^{1/3} \tag{3}$$

where P = pressure (bar), t = time (s), V = volume (m^3), K_{St} = deflagration index (bar • m/s).

LOC was determined according to the standard EN 14034–4:2004+A1:2011 (2011) (European Committee for Standardization, 2011b) , in a variable nitrogen atmosphere. Two 1 kJ chemical Sobbe's Ignitors (EBBOS ChZ Fr. Sobbe Gmbh, Dortmund, Germany) were used as ignition sources.

3. Results and discussion

3.1. Biomass characterization

The analyzed samples showed moisture values between 2 and 8 % wet-based. Table 3 reports the results in terms of moisture, ashes, and volatile matter for the four most representative SCG-derived biomasses, i.e., native SCG, SCG pre-treated by HPTE, SCG pre-treated by RE (sample A5), and SCG pre-treated by HPTE and RE (sample B5).

Results about native SCG were in accordance with those available in literature (Inayat et al., 2022; Pujol et al., 2013). As confirmed by the

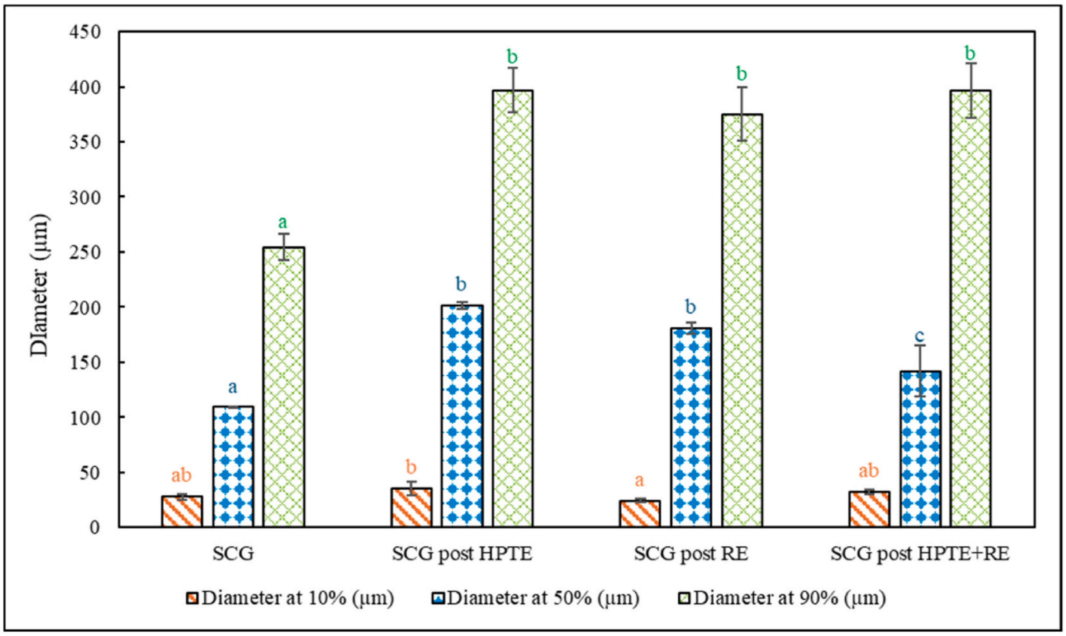

Fig. 2. Particle sizes for native spent coffee grounds (SCG), exhaust SCG after High Pressure and Temperature extraction (SCG post HPTE), exhaust SCG after reflux extraction (SCG post RE) (sample A5), and SCG post HPTE and RE (sample B5). Different letters correspond to significant statistical differences among data at each fermentation time ($p < 0.05$, Tukey's HSD post-hoc multiple comparison test). Different colors correspond to statistical analyses performed with different sets of data.

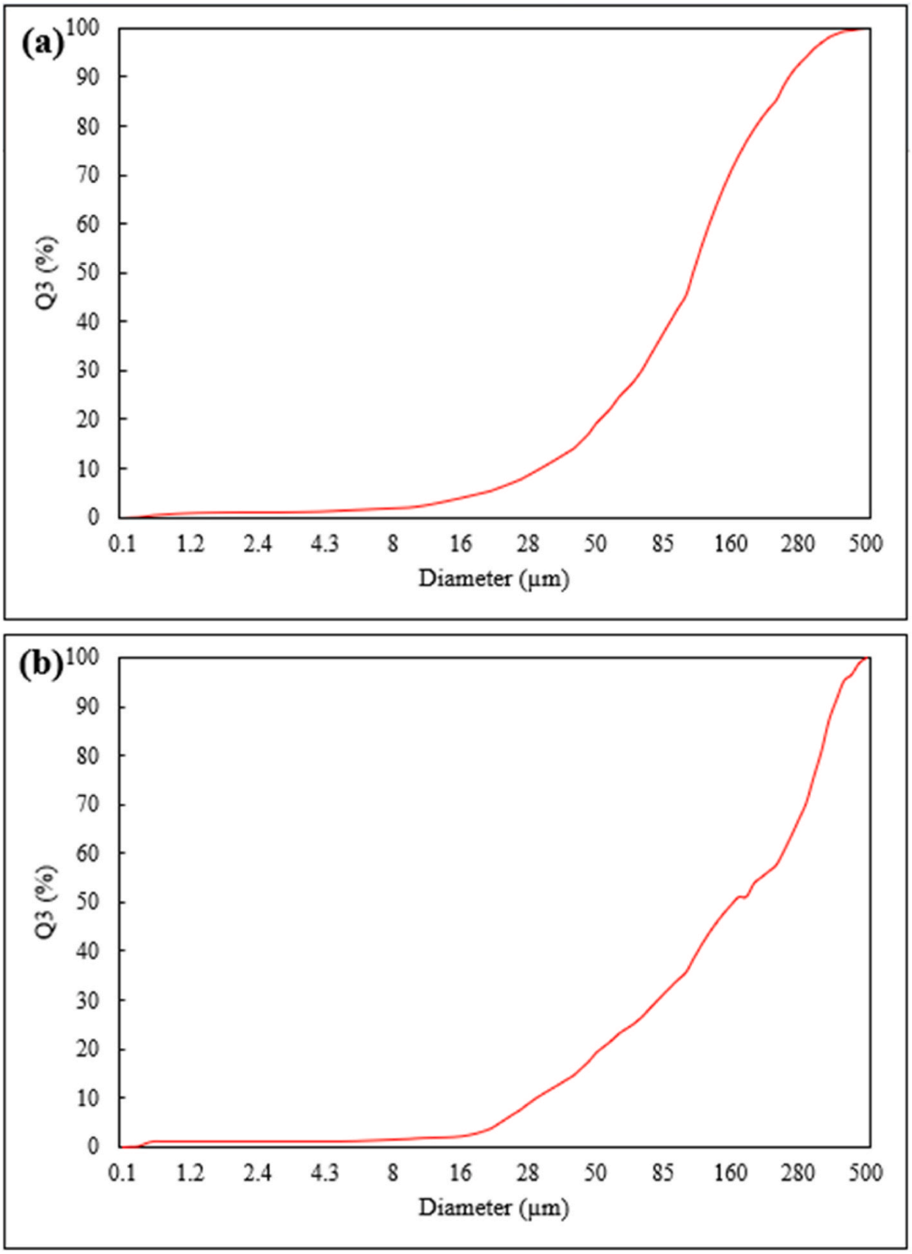

Fig. 3. Cumulative functions (*Q3*, %) for: **(a)** native spent coffee grounds (SCG) and **(b)** exhaust SCG after High Pressure and Temperature Extraction and Reflux Extraction (SCG post HPTE and RE (sample B5)).

statistical analysis, the pre-treatments by HPTE and RE led only to slight differences in terms of ashes, and volatiles. This implies that compounds extracted in these first stages of a potential biorefinery based on SCG represent only a small percentage of the global composition of SCG, leaving room for other applications for the biomass after antioxidants and lipid recovery (Pettinato et al., 2023). This result is in agreement with what reported by Ballesteros et al. (2014), who determined more than 50 % of insoluble dietary fibers in the composition of dry SCG.

Conversely, samples revealed statistically significant differences in their particle size distributions. Table 4 reports the SCG particle sizes when the cumulative function reached 10 %, 50 %, and 90 % (D_{10}, D_{50}, and D_{90}, respectively). As better visualized in Fig. 2, the cumulative functions of the most representative samples (SCG, SCG post HPTE, SCG post RE (sample A5), and SCG post HPTE and RE (sample B5)), revealed slightly lower size fractions for SCG, with respect to the pre-treated powders. In particular, the largest sizes were obtained after pre-treatments, probably due to the SCG structure variation after the interaction with water and the organic solvents. The obtained results were in line with the literature data for SCG, reporting mean particle diameters of 225–450 μm (Go et al., 2016; Loyao et al., 2018; Massaro Sousa and Ferreira, 2019) and D_{90} ranging between 300 and 400 μm (Bejenari et al., 2021). Little discrepancies from literature results could be related to different coffee varieties, moisture contents, and equipment.

The cumulative functions (*Q3*, %) of two most representative samples, native SCG and SCG pre-treated by HPTE and RE (sample B5), are depicted in Fig. 3. In contrast to native SCG, powders subjected to two subsequent extractions did not present an unimodal distribution, as confirmed by several points of flex in the cumulative curve (Fig. 3b), demonstrating that the pre-treatment steps led to the formation of isolated groups of both coarser and finer particles. These behaviors can be explained by the simultaneous occurrence of two opposite effects, i.e., erosion of particles due to violent contacts at high temperatures and increased fragility due to subsequent drying steps, and more stable

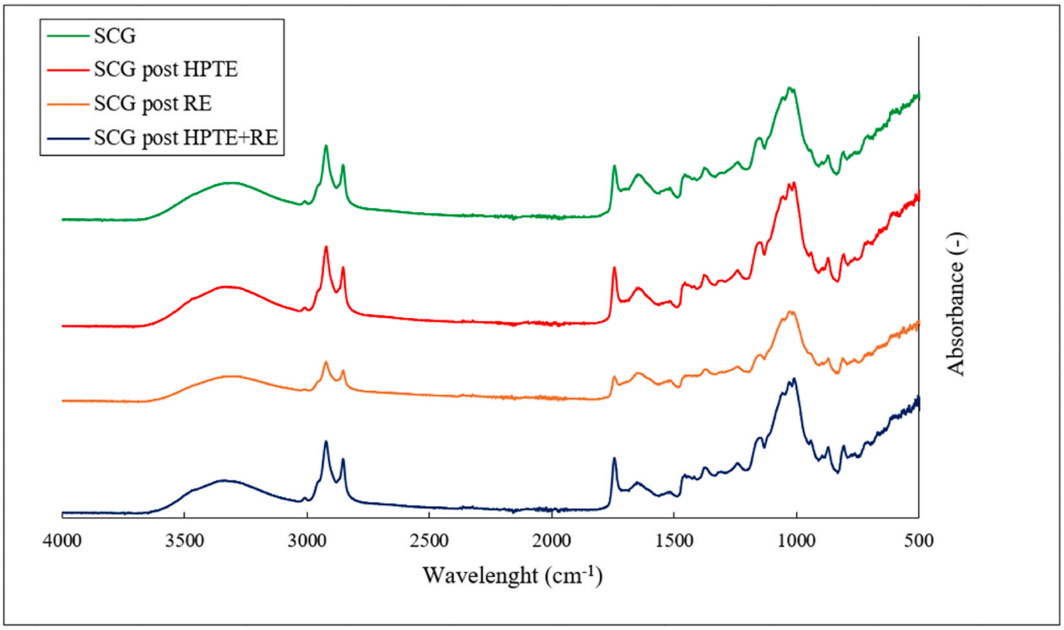

Fig. 4. ATR-FTIR spectra for native spent coffee grounds (SCG), exhaust SCG after High Pressure and Temperature Extraction (SCG post HPTE), exhaust SCG after Reflux Extraction (SCG post RE) (sample A5)), and exhaust SCG after High Pressure and Temperature Extraction and Reflux Extraction (SCG post HPTE + RE) (sample B5)).

agglomeration of the finer particles to larger ones, leading to higher size of agglomerates particles than in native SCG. The larger the number of particles of finer size, the higher the risk of fire and explosion along the plant, even if the agglomeration phenomenon works as partial compensation.

Regarding the biomasses chemical composition, it was investigated through ATR-FTIR. The most representative samples were analyzed and are shown in Fig. 4, ie., native SCG, SCG pre-treated by HPTE, SCG pre-treated by RE (sample A5), and SCG pre-treated by HPTE and RE (sample B5).

The FTIR spectra of the four tested biomasses showed almost the same characteristic bands. More than 800 compounds are present in spent coffee, including linear and branched molecule structures and more complex cyclic and heterocyclic ones (Wang et al., 2009). Specifically, at 3308 cm^{-1} a characteristic broad peak associated with the stretching of O-H functional groups was identified. This was probably related to inter- and intra-molecular hydrogen bonding of several polymeric compounds such as cellulose and lignin (Bejenari et al., 2021). The presence of caffeine was detected thanks to the presence of two sharp peaks at 2922 and 2852 cm^{-1}, associated to the symmetric and asymmetric C-H stretching vibration of methyl groups, respectively (Vahabi et al., 2021). These peaks, as well as those found at 3006 cm^{-1}, indicating the stretching of C-H olefinic groups, can be also associated with the presence of aliphatic chains in lipids, present in native SCG and pre-treated by HPTE. Furthermore, the characteristic peak of the carbonyl (C=O) ester group vibration at 1743 cm^{-1} further confirmed the presence of triglycerides and/or aliphatic esters (Craig et al., 2012a). The band at 1240 cm^{-1}, typical of the stretching of C-O group, was identified as one of the most characteristic peaks for caffeine (Craig et al., 2012b). Finally, the stretching vibration of C=C bond in the aromatic ring structure was identified in the 1646 cm^{-1} peak, reporting the presence of the caffeine carbonyl group (Bejenari et al., 2021). Chlorogenic acids, like caffeic, p-coumaric, and ferulic acids, were also identified, showing strong absorption bands in the 1450-1000 cm^{-1} region, including axial C-O deformation of quinic acid (1085-1050 cm^{-1}), O-H angular deformation (1420-1330 cm^{-1}), and C-O-C ester bond (1300-1000 cm^{-1}) (Craig et al., 2012a, 2012b). The presence of aromatic structures was further verified by peaks in the 900-670 cm^{-1} range, indicating possible C-H groups with aromatic out-of-plane bend (Li et al., 2014). The 1400-900 cm^{-1} region was characterized by the vibration of several types of bands, including C-H, C-O, C-N, and P-O vibrations, related to the presence of carbohydrates (Craig et al., 2012b), confirmed by other peaks in the 950-700 cm^{-1} range (Bejenari et al., 2021). Two sharper peaks were detected at 1029 and 1007 cm^{-1}, indicating the presence of glycosidic bonds in galactomannan and polysaccharides (Susilayati et al., 2022).

As for FTIR, thermogravimetric analysis was performed on the four most representative samples (native SCG, SCG pre-treated by HPTE, SCG pre-treated by RE (sample A5), and SCG pre-treated by HPTE and RE (sample B5)). Fig. 5 shows the TG, DTG, and DSC curves for the four tested powders, which reported a similar decomposition trend.

The results recorded four decomposition stages, in accordance with those in literature (Colantoni et al., 2023; Fermoso and Mašek, 2018; Leow et al., 2021; Primaz et al., 2023). The first one, ranging between the initial temperature and 175 °C, comprised a mass loss associated with free and bound moisture release. Subsequently, an increase in the heat exchange process was determined between 200 °C and 330 °C, where a narrow peak was recorded in DTG, representing the decomposition of light volatiles like hemicellulose. Finally, cellulose and lignin characteristic peaks were identified at about 330 °C and 380 °C, respectively. Indeed, SCG presents a large difference in cellulose and lignin content, making it possible to distinguish between two maximum degradation rates, that, instead, commonly overlap (Fermoso and Mašek, 2018). They represent the most stable and complex biopolymers comprised in the examined biomass, constituting the main rate limiting factor in the thermochemical decomposition of SCG (Fermoso and Mašek, 2018; Leow et al., 2021). Albeit HPTE and RE could have an impact on the biomass structure, as demonstrated by the particle size distribution results, no significant differences can be observed among samples. Indeed, slight variabilities are present, but they can be traced back to samples heterogeneity.

3.2. *Explosion properties of the SCG-derived biomasses*

Explosivity properties of the SCG biomasses were evaluated in terms of *MIT*, *MIE*, P_{max}, $(dP/dt)_{max}$, K_{St}, and *LOC*.

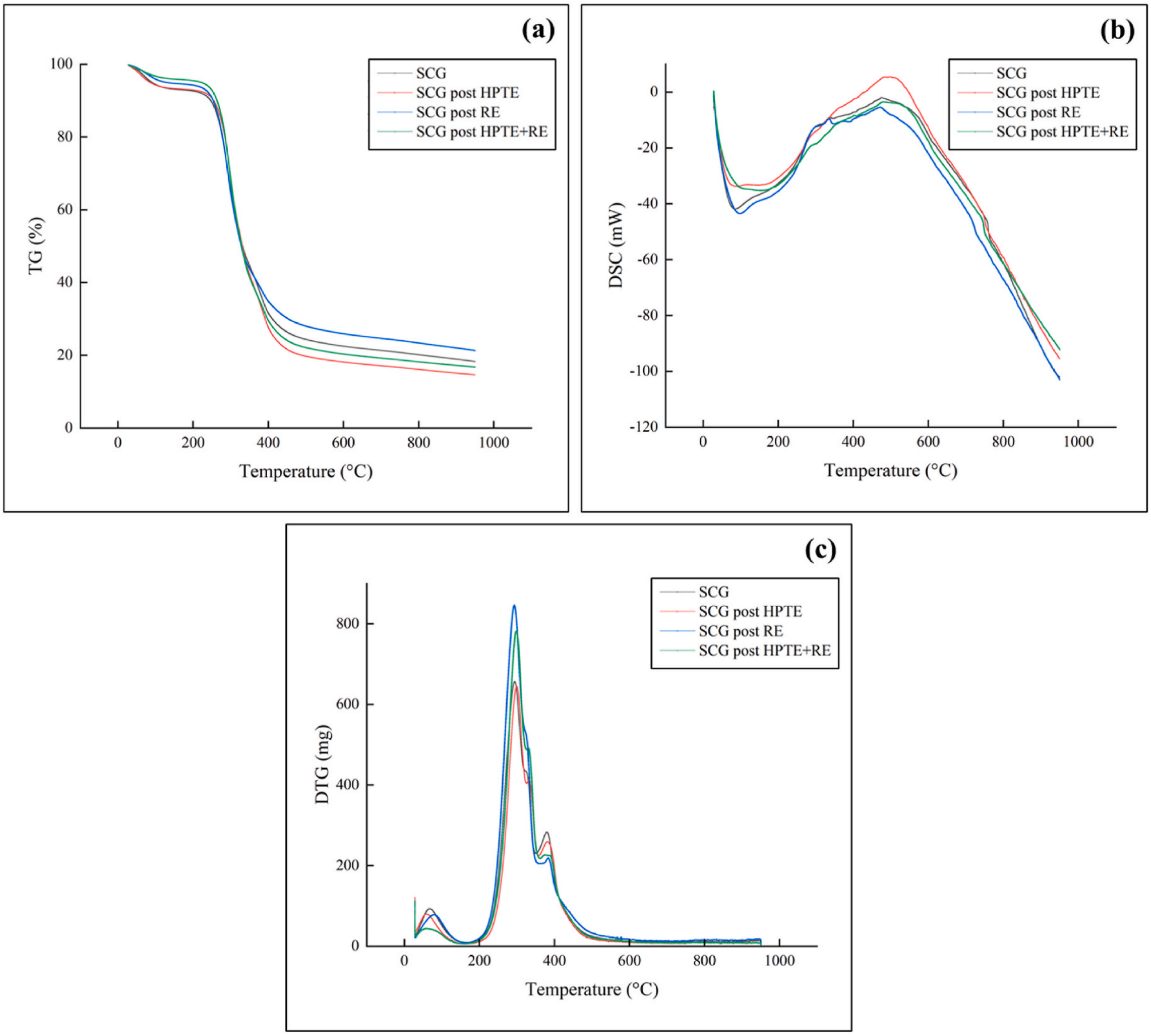

Fig. 5. **(a)** TG, **(b)** DSC, and **(c)** DTG for native spent coffee grounds (SCG), exhaust SCG after High Pressure and Temperature Extraction (SCG post HPTE), exhaust SCG after reflux extraction (SCG post RE) (sample A5), and exhaust SCG after High Pressure and Temperature Extraction and Reflux Extraction (SCG post HPTE +RE) (sample B5).

MIT for both dust clouds (*MIT*$_{cloud}$) and dust layers (*MIT*$_{layer}$) were evaluated for all SCG samples by means of a specific furnace and a heating surface plate, respectively.

Table 5 summarizes the *MIT* results for all the examined samples in the size range of 0–500 μm, in agreement with those in literature for spent coffee grounds and other biomass types.

High values for both *MIT*$_{cloud}$ and *MIT*$_{layer}$ were recorded for all tested powders. Results agreed with those reported in literature for SCG and other biomass wastes presenting similar moisture contents and particle size distributions (Fernandez-Anez et al., 2014; García Torrent et al., 2016; Portarapillo et al., 2021; Ramírez et al., 2009; Wachter et al., 2016). Indeed, the volatilization of hemicellulose, the more unstable compound in SCG, represented the main contribution to volatiles, giving mainly CO_2, mostly produced by extrusion of carbonyl and carboxyl groups (Zhao et al., 2017), which do not present a significant impact on flammability and explosion propagation (Danzi et al., 2021). On the contrary, cellulose and lignin commonly generate flammable volatiles like CO, CH_4, and H_2, which are originated from the biopolymers carbonyl groups, methoxyl groups, C=C, and C-H bonds, respectively (Danzi et al., 2021; Fermoso and Mašek, 2018), but at higher temperatures, as attested by the TGA results (see Section 3.1). This feature made the powders less sensitive to ignition. SCG minimum ignition temperature was recorded equal to 460 °C for dust clouds and 290 °C for dust layers, respectively. According to literature (Pietraccini et al., 2021; Portarapillo et al., 2021), at temperatures lower than 500 °C, dust did not instantaneously ignite in clouds, but after 2–3 s. This was probably due to the fact that the flame was generated by the ignition of the biomass off-gases, like CO and CH_4. A pre-treatment step by HPTE affected the SCG structure and particles dimensions, leading to a slightly higher availability of cellulose and lignin, as well as volatile matter, mostly prone to enhance the flame propagation. *MIT* of SCG samples, pre-treated by HPTE and by both HPTE and RE, was reduced to 420 °C. An intermediate *MIT*$_{cloud}$, equal to 440 °C, was obtained for SCG samples pre-treated by RE. All samples deriving from the same extraction method approximately showed the same *MIT* results, indicating that little variations in operating conditions had no impact on the flammability behavior. Regarding *MIT*$_{layer}$, it ranged between 290 °C and 300 °C for all tested samples. As the surface temperature increased, the samples heating was faster, as well as the decomposition of cellulose and lignin, representing the limiting step to flame propagation, with subsequent ignition of the layer surface. For temperatures higher than 300 °C, all powders are carbonized (Fig. 6).

A glass Hartmann tube was used for the evaluation of *MIE* for all SCG samples. *MIE* values were higher than 3000 mJ for all the tested samples, as shown in Table 6. This behavior could be directly associated with the high hemicellulose content in SCG, whose decomposition leads to low

Table 5

Minimum Ignition Temperature (*MIT*) for dust clouds and layers of SCG samples and other characteristic biomasses investigated in literature.

Sample	MIT_{cloud} (°C)	MIT_{layer} (°C)	Ref.
SCG	460	290	This study
SCG post HPTE	420	300	
A1	440	290	
A2	440	290	
A3	440	290	
A4	440	290	
A5	440	290	
A6	440	290	
A7	440	300	
B1	420	290	
B2	420	300	
B3	420	290	
B4	420	300	
B5	420	290	
B6	420	300	
B7	420	290	
SCG	470	310	Wachter et al. (2016)
Grape pomace	480	290	Portarapillo et al. (2021)
Barley grain dust	480	290	Ramírez et al. (2009)
Orange peel	440	300	García Torrent et al. (2016)
Dried sewage sludge	480	300	Fernandez-Anez et al. (2014)

reactive volatile gases, like CO_2 (Danzi et al., 2023). The same results were obtained by Todaka et al. (2016) for both oil-retaining SCG and oil-extracted SCG. Similar outcomes were determined for other biomasses investigated in literature (Fernandez-Anez et al., 2014; Pietraccini et al., 2021; Portarapillo et al., 2021; Ramírez et al., 2009; Todaka et al., 2016), demonstrating a low risk level associated with these material types, according to EN ISO/IEC 80079-20-2:2016 (2016) (International Organization for Standardization International Electrotechnical Commission, 2016a). Indeed, *MIE* values higher than 1000 mJ commonly account for substances with a low sensitivity to ignition by electrical discharge. However, it is noteworthy accounting for sample ageing which could reduce *MIE* due to an increase in cellulose content. Ageing evolution requires careful consideration especially when prolonged storage is designed for the process (Danzi et al., 2023).

The explosion pressure (P_{ex}) associated with the SCG samples was measured by means of a 20 L explosion chamber, with the aim of

Table 6

Minimum Ignition Energy (*MIE*) of SCG samples and other characteristic biomasses investigated in literature.

Sample	*MIE* (mJ)	Ref.
SCG	>3000	This study
SCG post HPTE	>3000	
SCG post RE (samples A1-A7)	>3000	
SCG post HPTE + RE (samples B1-B7)	>3000	
Oil-retaining SCG	>3000	Todaka et al. (2016)
Oil-extracted SCG	>3000	
Grape pomace	>1000	Portarapillo et al. (2021)
Olive pomace	>1000	Pietraccini et al. (2021)
Barley grain dust	>1000	Ramírez et al. (2009)
Dried sewage sludge	>1000	Fernandez-Anez et al. (2014)
Cellulose	407	Todaka et al. (2016)

Table 7

Explosion parameters (maximum explosion pressure (P_{max}), maximum rate of pressure rise ($(dP/dt)_{max}$), dust deflagration index (K_{St}), limiting oxygen concentration (*LOC*)) of SCG samples and other characteristic biomasses investigated in literature.

Sample	P_{max} (bar)	$(dP/dt)_{max}$ (bar/s)	K_{St} (bar • m/s)	*LOC* (% O_2)	Ref.
SCG	7.0	77.5	21.0	19.5	This study
SCG post HPTE + RE (sample B5)	7.5	129.2	35.1	19.5	
Grape pomace	6.2	212.9	57.8	–	Portarapillo et al. (2021)
Olive pomace	5.9	78.8	21.0	–	Pietraccini et al. (2021)
Wheat grain	8.1	544.0	148.0	–	Ramírez et al. (2009)
Barley grain	7.1	185.0	50.0	–	
Orange peel	7.3	469.0	127.0	–	García Torrent et al. (2016)
Wheat flour	7.3	82.8	54.9	–	Kuracina et al. (2019)
Dried sewage sludge	6.1	125.0	33.9	15.0	Fernandez-Anez et al. (2014)

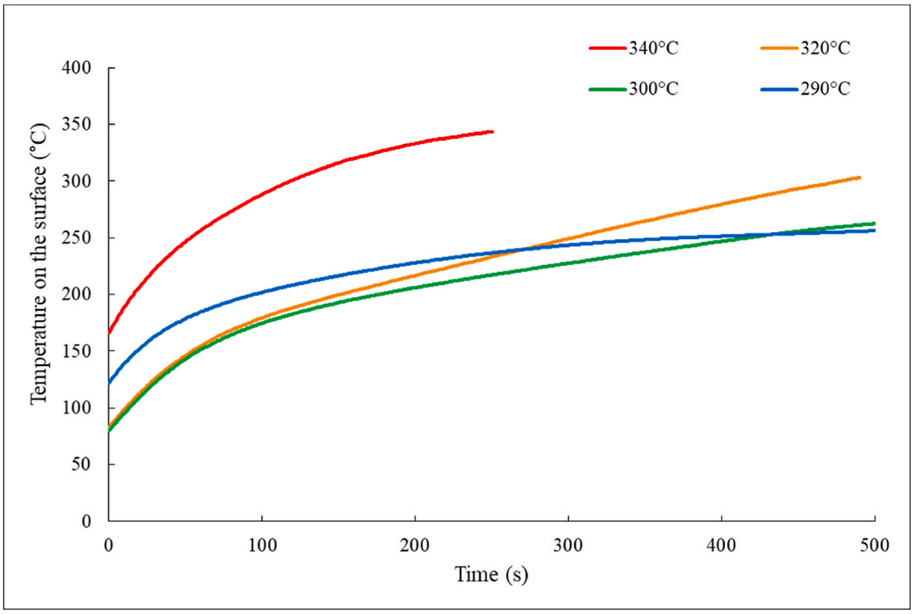

Fig. 6. Temperature dependance of the SCG layer surface on the time of exposure to a hot plate set on four different temperatures (340 °C, 320 °C, 300 °C, 290 °C).

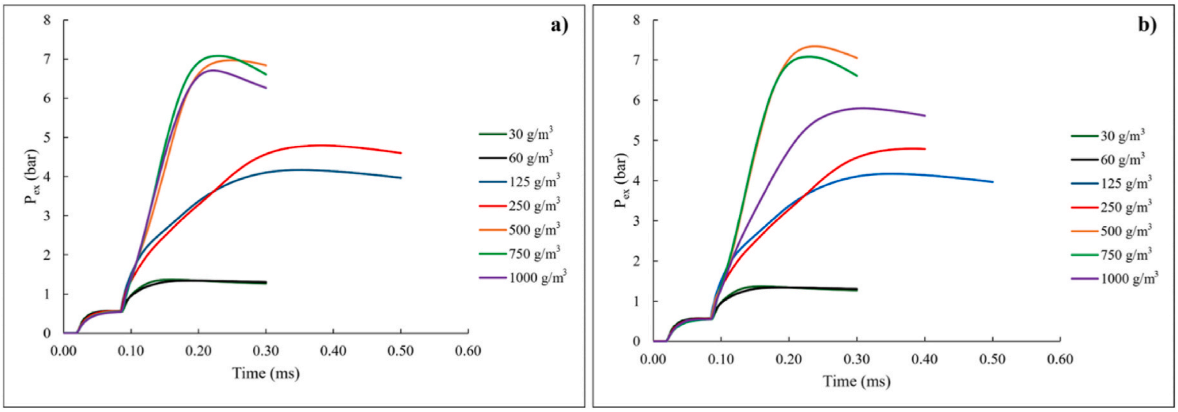

Fig. 7. Pressure trend (P_{ex}) in the 20 L explosion chamber for **(a) native spent coffee grounds**(SCG) and **(b) exhaust spent coffee grounds after High Pressure and Temperature Extraction and Reflux Extraction** (SCG post HPTE +RE) (sample B5).

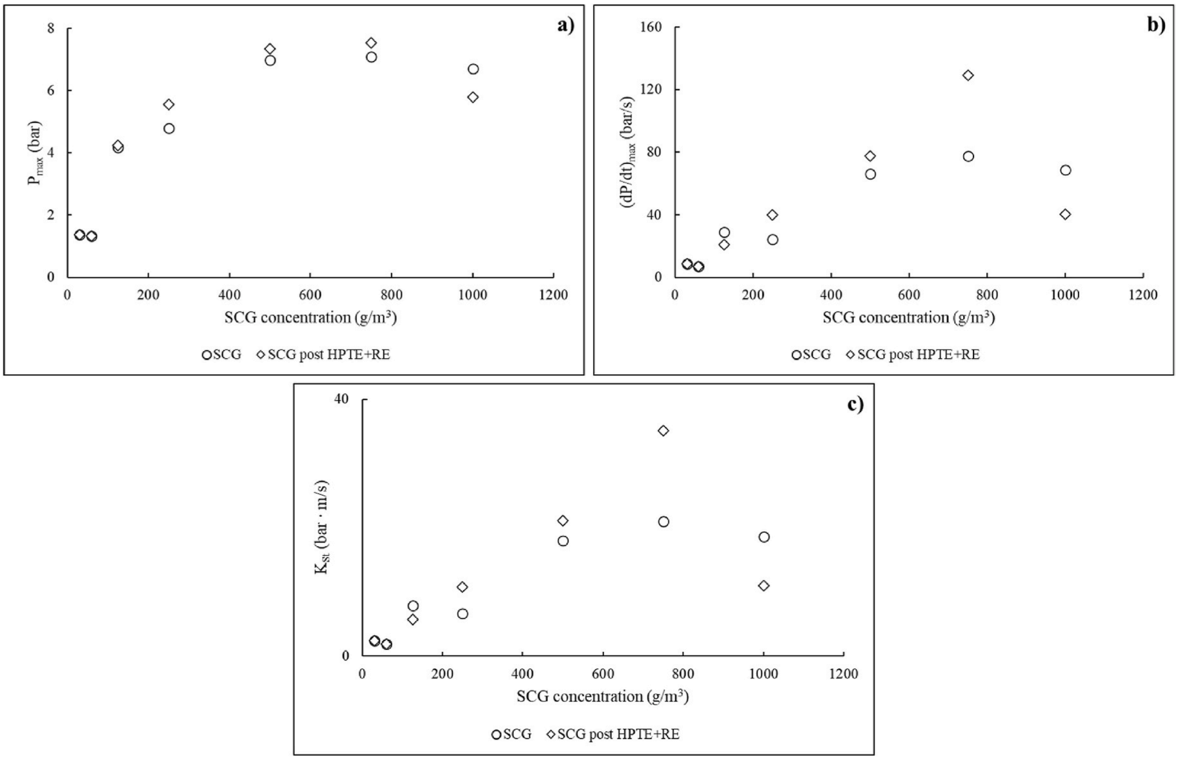

Fig. 8. **(a)** P_{max}, **(b)** $(dP/dt)_{max}$, and **(c)** K_{St}, as a function of SCG concentration inside the 20 L explosion chamber.

defining the main parameters to be considered in the phase of process scale-up and developing of explosion risk prevention and protection systems.

Since the powders pre-treated through the same extraction methodologies, but at different operating conditions, did not present appreciable changes in terms of *MIT* and *MIE*, the explosion parameters were determined for the most two significant samples, i.e., native SCG and SCG pre-treated by HPTE and RE (sample B5). Table 7 reports the obtained results in terms of P_{max}, $(dP/dt)_{max}$, K_{St}, and *LOC* for the tested samples and a comparison with other similar biomasses investigated in literature.

Both SCG as such and SCG post HPTE and RE presented P_{max} and $(dP/dt)_{max}$ values at a dust concentration inside the explosion chamber equal to 750 g/m^3 (Figs. 7 and 8).

Such outcomes were in line with those presented in literature for other biomass types, comprising them into the safest explosion class *St1*, in accordance with the Occupational Safety and Health Administration (OSHA) (Occupational Safety and Health Administration, 2009). Slightly higher values for P_{max}, $(dP/dt)_{max}$, and K_{St} were recorded for SCG pre-treated by HPTE and RE, associated with a high dust sensitivity to reactivity and ignition, although not compromising the overall safety of the pre-treated powders. Indeed, as previously discussed for *MIT*, the SCG structure and particle size were probably affected by the pre-treatments: slightly higher volatile matter, cellulose, and lignin contents were associated to higher flame propagations. Regarding *LOC*, a value of 19.5 % was recorded for both powders, while lower oxygen values did not lead to flame propagation.

Considering the obtained outcomes, the SCG-derived biomasses presented low hazard levels in terms of flammability and explosiveness susceptibility, placing this dust category in line with others investigated in literature, such as grape pomace, barley grain, and wheat flour.

The obtained results provide a valuable insight towards the definition of a conceptual methodology to preliminary design safety protocols and industrial good practices tailored to selected biomasses in the form of dust. Starting from material handling, the presence of a drying unit is expected to stabilize wet matrices like SCG, whose initial moisture content is about 60–70 %. Although SCG revealed to be less combustible than other industrial powders, if dried and pulverized, it can lead to dust explosion hazards under confined and oxygen-rich conditions. Following the ATEX (European Parliament and Council Directive, 2014) and OSHA (Occupational Safety and Health Administration, 2009) guidelines for combustible dust handling, reliable prevention measures including good ventilation, ignition source avoidance, and flammable solvent contact limitation should be ensured throughout SCG processing, by enforcing an effective Safety Management System (SMS) (Markowski et al., 2021). The present study characterized raw materials, intermediates, and products present in the form of solid dust throughout the proposed SCG treatment process. The defined experimental procedure will be expanded to include the analysis of the flammability and explosiveness properties associated to all materials involved in the processing lines and unit operations, including solutions and suspensions, at their relative operating conditions.

4. Conclusions

In recent times, numerous industries focused their attention on biomass loading, storing, handling, and discharging processes, increasing the need for safety measures against fire and explosion risks.

This work dealt with the characterization of SCG in terms of flammability and explosion properties as a function of the process steps they are subjected to. SCG were analyzed both in native form and after extraction and drying procedures, properly selected to recover valuable compounds, such as antioxidants and lipids. The solid matrices showed a change in particle size distribution after extraction processes but no significant differences in the thermal behavior. Pre-treated dust was associated with a higher sensitivity to ignition, reporting lower values for MIT_{clouds} (420–440 °C). In general, all samples deriving from the same extraction method reported the same *MIT* results, demonstrating that little variations in the operating conditions did not affect the flammability behavior, within the sensitivity of the analytical instrument. In addition, all tested powders were not subjected to ignition by electrical discharge with an energy of up to 3000 mJ, probably due to the high hemicellulose content in SCG, whose decomposition leads to low reactive volatile gases, like CO_2. Results deriving from experiments in the 20 L explosion chamber embedded SCG dust in the explosion class *St1*, reporting K_{st} values lower than 100 bar m/s. Also in this case, samples pre-treated by both HPTE and RE were associated with a slightly higher explosion risk, showing P_{max} and K_{st} values of 7.5 bar and 35.1 bar m/s, respectively.

Although SCG powders are associated with low flammability and explosion hazards, the obtained results can have relevant implications on the specification of their safe storage, handling, and treatment conditions. With these regards, prolonged storage of dry biomass dust should be monitored. As a recommendation for industrial processing, good ventilation should be ensured during storage, as well as the elimination of possible ignition sources, according to ATEX and OSHA guidelines.

Future investigations will involve further characterization of the properties of materials involved in each process step. Indeed, the current study focused on raw materials, intermediates, and products present in the form of solid dust throughout the overall treatment process. As a future perspective, to overcome the limitations of this study, the research will be expanded to include the characterization of all materials, in all the forms involved in the processing lines and unit operations, at their actual operating conditions. A complete understanding of the hazards associated with these “non-traditional” dust and processes will be thereby fulfilled, allowing for an inherently safer working environment, within the greener-friendly processes era.

CRediT authorship contribution statement

Maria Bolla: Writing – original draft, Investigation, Formal analysis, Data curation. **Margherita Pettinato:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Vojtech Jankuj:** Writing – review & editing, Visualization, Methodology, Data curation, Conceptualization. **Jan Skrinsky:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Aleš Bernatik:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Patrizia Perego:** Writing – review & editing, Supervision, Funding acquisition. **Bruno Fabiano:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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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