CHEMICAL ENGINEERING TRANSACTIONS
VOL. 118, 2025
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Laura Piazza, Francesco Donsì, Giorgia Spigno, Paolo Ciambelli, Luca di Palma

**ISBN** 979-12-81206-19-9; **ISSN** 2283-9216
DOI: 10.3303/CET25118073

# Cocoa Powder and Explosion Risk: An Analysis of Components and Triggering Causes

Alessandro Pagano[a], Simone Gelosa[a], Antonella Mazzei[b], Sabrina Copelli[c,*]

[a] Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica, Via Mancinelli 7, 20131, Milano, Italy
[b] Innovhub Stazioni Sperimentali per l'Industria S.r.l., Via Galilei 1, 20097, San Donato Milanese (MI), Italy
[c] Università degli Studi dell'Insubria, Dipartimento di Scienza e Alta Tecnologia, Via Valleggio 9, 22100, Como, Italy
sabrina.copelli@uninsubria.it

Dust explosions represent a major hazard in food processing industries, particularly when dealing with organic powders. Cocoa powder, although widely produced and consumed, has received little scientific attention regarding its explosibility compared to other food powders such as flour or sugar. This work investigates the potential explosiveness of cocoa powder by analysing its chemical and physical properties and identifying the main parameters influencing ignition sensitivity. Five commercial cocoa powders were selected, and an experimental campaign consisting of thermogravimetric analysis (TGA), crystallization and melting studies using reaction calorimetry, granulometric analysis, ICP-MS for metallic content, and pH/colorimetric analysis was carried out. A Matlab-based fitting model was developed to extract kinetic constants from TGA data, while a second code was implemented to calculate the theoretical Minimum Ignition Energy (MIE) from the collected experimental data. Results show that kinetic constants, crystallization enthalpies, particle size distribution, and metallic content significantly influence cocoa powder explosiveness. In particular, the presence of potassium carbonate/hydroxide and aroma additives can alter ignition susceptibility with respect to pure cocoa powders. The correlation between metal content (notably Al and Mg), pH, and colour was confirmed, indicating that darker powders with higher alkalinity may present lower ignition sensitivity. The theoretical protocol for MIE estimation developed in this work provides a valuable predictive tool that can reduce the need for extensive practical testing, also contributing to both the understanding of cocoa powder explosiveness and the safer handling of such powders in food industries.

## 1. Introduction

Dust explosions are a well-known risk in process industries handling combustible powders such as coal, wood, starch, flour, and sugar (Bartknecht, 1989; Eckhoff, 2003). The hazard arises when a combustible powder is dispersed in air, forming an explosive atmosphere that can be ignited by a sufficiently strong energy source. Deflagration index ($K_{st}$) and Minimum Ignition Energy (MIE) are the most critical parameters used to evaluate either the explosion violence or the sensitivity to catch fire of powders.

Food dusts are of particular concern as they are handled in large quantities and often stored in silos or conveyed pneumatically, conditions that promote dust cloud generation (Amyotte and Eckhoff, 2010). Among food powders, cocoa powder is widely produced and consumed, yet its explosibility characteristics have received limited scientific investigation. While extensive studies completed with mathematical modelling exist for other organic powders (e.g., wheat flour, maize starch, milk powder, etc..) (Fumagalli et al., 2017; Scotton et al., 2020), research on cocoa powder explosibility is scarce.

Cocoa powder is a complex substance containing carbohydrates, fats, proteins, minerals, and minor compounds. Its composition varies depending on processing methods (alkalization, roasting, fat removal, addition of flavouring agents). These variations may significantly influence explosibility, as parameters such as fat content, particle size distribution, fat crystallization behaviour, and metallic impurities directly affect the dust flammability.

Paper Received: 25 August 2025; Revised: 15 September 2025; Accepted: 02 October 2025
Please cite this article as: Pagano A., Gelosa S., Mazzei A., Copelli S., 2025, Cocoa Powder and Explosion Risk: an Analysis of Components and Triggering Causes, Chemical Engineering Transactions, 118, 433-438 DOI:10.3303/CET25118073

The objective of this study was twofold: a) to investigate how the physical and chemical characteristics of cocoa powders can influence their explosibility; and b) to develop a theoretical protocol for estimating the MIE of cocoa powders using kinetic and thermophysical data, thereby reducing the reliance on costly and time-consuming experimental testing.
Moreover, the work integrated, for the first time, information coming from different calorimetric and analytical techniques: thermogravimetric and crystallization analyses with granulometry, ICP-MS, and pH/colorimetric tests. A fitting algorithm was also developed to extract kinetic constants from thermogravimetric curves, and a second code was implemented for theoretical MIE calculation (making use of the kinetic constants estimated using processes thermogravimetric data). Five commercial cocoa powders were tested, providing a diverse dataset of processing conditions and compositions.

## 2. Materials and Methods

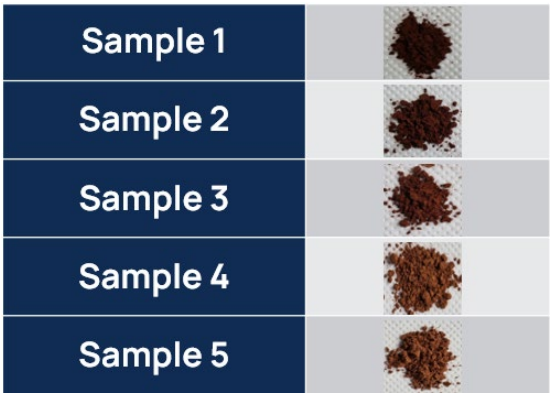
### 2.1 Cocoa samples

Five commercial cocoa powders were selected for analysis (see Table 1), to take into account different production processes (e.g., roasting operations at different temperatures and for different times) and compositions (in terms of additives). Two cocoa butters were used as references in crystallization studies.

*Table 1: List of cocoa powder samples used in the study.*

| Sample | Brand | Characteristics | Fat Content [%] | Additives/Notes |
|---|---|---|---|---|
| 1 | Perugina | Extra Dark | 23 | KOH/$K_2CO_3$ added |
| 2 | Lindt | Patisserie | 31 | KOH/$K_2CO_3$ added |
| 3 | Perugina | Bitter Cocoa | 21 | Contains aroma |
| 4 | Good Nutritions | Organic Pure | 11 | Pure cocoa |
| 5 | NaturaleBio | Organic Raw | 11 | Pure, from raw beans |

Figure 1 shows the appearance of all the tested cocoa powders. Particularly, all powders displayed clear visual differences: Samples 1 and 2 had a dark brown colour, typical of alkalized cocoa with higher pH, while Samples 4 and 5 were lighter, consistent with lower alkalinity and fewer processing steps. Sample 3 stood out due to added aromas and slightly higher salt content, making it more representative of “ultra-processed” cocoa powders. Visual inspection alone hinted at compositional differences likely to affect explosion sensitivity, an aspect confirmed by RGB colour analysis.




| | *Red* | *Green* | *Blue* |
|---|---|---|---|
| ***Sample 1*** | 60 | 28 | 19 |
| ***Sample 2*** | 72 | 29 | 19 |
| ***Sample 3*** | 111 | 51 | 32 |
| ***Sample 4*** | 126 | 63 | 32 |
| ***Sample 5*** | 147 | 83 | 50 |

*Figure 1: Cocoa powders analysed in this study (Samples 1–5). Appearance and rgb colour determination.*

### 2.2 Analytical characterisation

Thermogravimetric Analyses (TGA) were performed starting from 30 °C up to 500 °C, with a heating rate of 5 °C/min and a nitrogen flux of 10 L/min, to determine weight loss due to pyrolysis (and the eventual water content). Data were processed with a Matlab code to determine kinetic constants (pre-exponential factor A, activation energy $E_a$, reaction order n, and correction factor k) by a minimum least square algorithm.
Crystallization and melting enthalpies of the different cocoa powders were evaluated using an EasyMax 102™ workstation (Mettler Toledo) to calculate the cocoa butter content of the powder. Particularly, two reference cocoa butters (The Soapery and MP Biomedicals) were used as blank measures of the enthalpies of crude

cocoa butter and then, all cocoa powders were tested in 1:1 w/w mixtures with the two different cocoa butter to facilitate melting. The testing procedure consisted in heating the mixture till 45-50 °C and then performing a cooling operation where the jacket temperature was set at 20 °C, to provide the formation of type IV crystals. In all experiments the formation of crystals of type V was also observed.
A Malvern Mastersizer 3000 was used to determine particle size distribution of each cocoa powder; such information was necessary to calculate the Minimum Ignition Energy (MIE) in a further step.
Inductively Coupled Plasma Mass Spectrometry (ICP-MS) measures were done to determine the concentrations of metals as Al, Mg, Fe, Zn, and B, which are known to influence powder explosibility (Taveau et al., 2019; Wang et al., 2021).
pH of each cocoa powder was measured following the ICA method 15/1972 (ADM Cocoa, 2006). Moreover, colour was analysed with a Matlab-based image processing code, reporting RGB values (see Figure 1).

### 2.3 Theoretical MIE Calculation

A Matlab model was developed to calculate theoretical MIE values using all kinetic and thermophysical data derived from the experimental campaign (particularly, enthalpy of pyrolysis, crystallization enthalpy, particle size distribution, kinetic parameters of pyrolysis, etc.. were used). All the equations can be found in Scotton et al. 2020. Ignition energy levels spanning from 1 to 1000 mJ were simulated for MIE determination in accordance with the standard procedure ASTM E2019 used with a Hartmann-type apparatus (e.g. MIKE 3).

## 3. Results and Discussion

### 3.1 Kinetic Analysis

All thermogravimetric curves were processed to be converted in normalised conversion curves. Figure 2 reports a comparison between experimental (red dotted) and fitted (black continuous) curves for all samples. Particularly, a good agreement between experimental and fitted values can be observed in the central part of the conversion curve, validating the robustness of the Matlab algorithm.

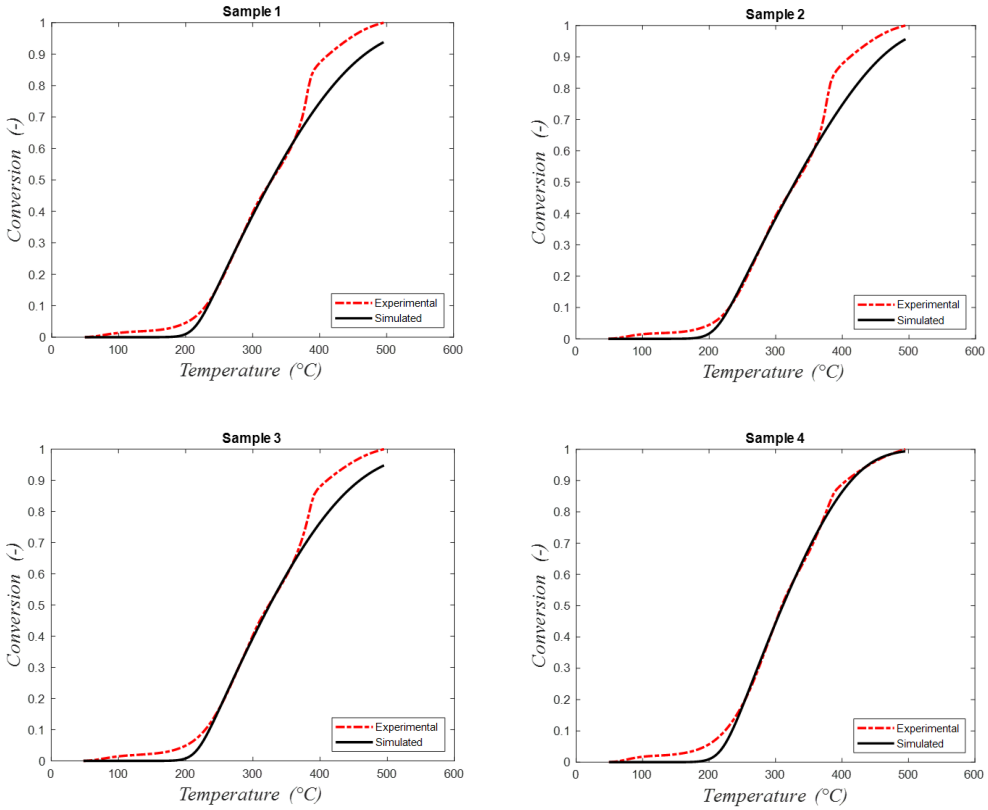



*Figure 2: Experimental vs. theoretical TGA curve for all dust samples. (continue)*

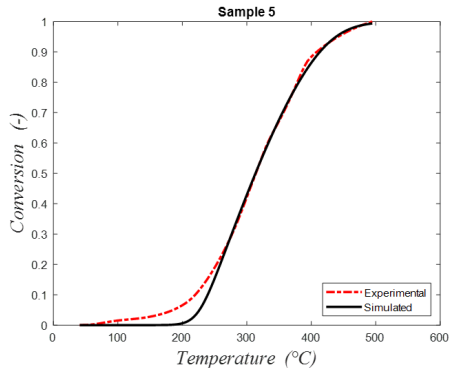



*Figure 2: Experimental vs. theoretical TGA curve for all dust samples.*

It is important to justify because only the central part of the conversion curve was used to fit the pyrolysis kinetic parameters. But, before, it is necessary to highlight that, three distinct thermal regions can be observed for each test: (i) evaporation of moisture up to ~200 °C, (ii) primary pyrolysis between 200–350 °C, and (iii) decomposition of minor components beyond 350 °C. As the loss of moisture due to heating cannot be modelled so easily and it is a moderate endothermic process with respect to pyrolysis, it was decided to consider relevant, for ignition purposes, only the central pyrolysis range. This is the reason because the fitting parameters were evaluated considering a perfect agreement among the different conversion curves only in the central region of the investigated temperature range. Table 2 highlights that A and $E_a$ values are of the same order of magnitude as those reported for other organic powders such as wheat flour and cellulose (Eckhoff, 2003). Interestingly, the correction parameter k decreased with increasing cocoa purity. This indicates that additives (e.g., $K_2CO_3$, KOH) increase the variability of decomposition kinetics, requiring stronger correction to fit the model. Pure powders (Samples 4–5) showed more predictable kinetic behaviour, consistent with fewer interfering compounds. This finding has industrial implications: powders with higher variability in decomposition kinetics may produce unpredictable ignition thresholds, rendering unreliable eventual explosion prevention measures.

*Table 2: Kinetic constants obtained from TGA analysis.*

| Sample | A [1/s] | $E_a$ [J/mol] | n [-] | k [-] |
|---|---|---|---|---|
| 1 | $9.30 \cdot 10^{15}$ | $1.920 \cdot 10^{5}$ | 3.00 | - 0.372 |
| 2 | $6.25 \cdot 10^{15}$ | $1.670 \cdot 10^{5}$ | 2.00 | - 0.420 |
| 3 | $7.30 \cdot 10^{15}$ | $1.920 \cdot 10^{5}$ | 3.00 | - 0.345 |
| 4 | $4.75 \cdot 10^{15}$ | $1.680 \cdot 10^{5}$ | 2.00 | - 0.295 |
| 5 | $7.53 \cdot 10^{15}$ | $1.720 \cdot 10^{5}$ | 2.00 | - 0.280 |

### 3.2 Crystallization behaviour

Cocoa powders have been melted by adding cocoa butter. Such cocoa butters (The Soapery and MB Biomedicals) were tested alone for the estimation of their specific heat capacity in liquid phase and their enthalpy of crystallization. Table 3 show the results, which find a good agreement with the current literature (Ioannidi et al., 2021).

*Table 3: Crystallization enthalpies, overall heat transfer coefficients and specific heat capacity for reference cocoa butters.*

| Sample | U [W/K·m²] | $c_p$ [J/gK] | $\Delta Q_{crist}$ [kJ] | $\Delta H_{crist}$ [J/g] |
|---|---|---|---|---|
| The Soapery | 82.086 | 1.7658 | 7.0648 | 141.3 |
| MP Biomedicals | 80.064 | 1.6921 | 6.6123 | 132.3 |

When the procedure described in paragraph 2.2 was applied to cocoa powders (Table 4), significant results emerged: Samples 1–3 had lower crystallisation enthalpies ($\Delta H_{crist}$) than Samples 4–5. This trend suggests that additives and processing reduce the latent heat associated with crystallization, possibly by disrupting the triglyceride matrix of cocoa butter.

*Table 4: Crystallization enthalpies of cocoa powder samples.*

| Sample | U [W/K·m²] | $c_p$ [J/gK] | $\Delta Q_{crist}$ [kJ] | $\Delta H_{crist}$ [J/g] |
|---|---|---|---|---|
| 1 | 59.452 | 1.5208 | 6.1502 | 102.50 |
| 2 | 50.450 | 1.3930 | 4.311 | 71.85 |
| 3 | 54.514 | 1.5099 | 5.4439 | 90.73 |
| 4 | 62.682 | 1.6718 | 5.8859 | 98.10 |
| 5 | 65.897 | 1.3605 | 6.3339 | 105.57 |

Conversely, purer powders displayed enthalpies closer to reference values, indicating more stable crystallization. From a safety perspective, crystallization enthalpy reflects how much energy can be released during cooling and storage. Powders with lower enthalpy may undergo less stable crystallization, potentially increasing the risk of exothermic events if improperly store. Thus, crystallization analysis provides not only compositional insight but also a proxy for evaluating thermal stability under industrial storage conditions.

### 3.3 Particle Size Distribution

Figure 4 reports the particle size distributions of the five cocoa powders tested within this work.

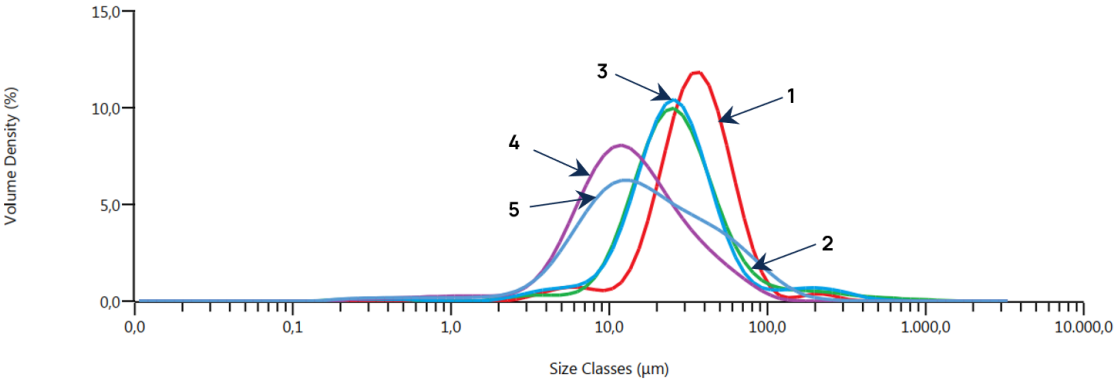



*Figure 4: Particle size distributions of the five cocoa powders.*

The particle size analysis revealed neat contrasts. Samples 1–3 clustered between 10–100 µm, while Samples 4–5 contained a significant fraction of fine particles below 10 µm. Literature indicates that particles below 50 µm are particularly hazardous as they can form stable dust clouds and ignite at lower energies (Bartknecht, 1989). The presence of ultrafine fractions in Samples 4–5 implies easier airborne dispersion, which, combined with their higher purity, could imply a relatively low MIE values. For industrial handling, this means pneumatic transport and dust filtration systems must be designed to capture fine fractions effectively, as these are the most prone to ignition.

### 3.4 Metallic Content and pH

Table 5 reports pH and concentrations of the most relevant metal ions into the different cocoa powder samples.

*Table 5: pH and main metal ions content of the 5 cocoa powder samples.*

| Sample | pH | Al [mg/kg] | Mg [mg/kg] | K [mg/kg] |
|---|---|---|---|---|
| 1 | 8.25 | 280.5 | 4904 | 36680 |
| 2 | 8.15 | 208.0 | 4530 | 41720 |
| 3 | 7.00 | 105.7 | 4967 | 34400 |
| 4 | 6.65 | 227.2 | 5202 | 31660 |
| 5 | 6.70 | 54.8 | 5463 | 15670 |

Samples 1 and 2, the darkest powders, had the highest alkalinity (pH ~8) and elevated aluminium concentrations. Darker colour correlated with higher alkalinity and metal content, consistent with the alkalization process where potassium salts are added.
Aluminium and magnesium are known to catalyse radical formation during pyrolysis (Wang et al., 2021; Zhang et al., 2020), lowering ignition thresholds. This could be responsible for alkalized powders of a lower theoretical

MIE value. Anyway, such a phenomenon could not be observed because these ions are usually present as salts. In contrast, Sample 5 showed the lowest Al concentration (54.8 mg/kg), consistent with its raw, minimally processed nature.

### 3.5 Theoretical MIE estimates

Table 6 reports the theoretically calculated MIE values for all the 5 analysed cocoa dusts.

*Table 6: Calculated MIE values for cocoa powder samples.*

| Sample | MIE [mJ] |
|---|---|
| 1 | 93 |
| 2 | 249 |
| 3 | 55 |
| 4 | 90 |
| 5 | 41 |

Theoretical MIE values varied across samples, with purer cocoa powders (Samples 4–5) showing slightly lower MIE (higher sensitivity), while alkalized powders (Samples 1–2) presented higher MIE, confirming the effect of processing additives in order to reduce the explosibility.

## 4. Conclusions

This study systematically investigated cocoa powder explosibility through analysis of kinetic, thermophysical, granulometric, and compositional properties. Particularly, cocoa powders showed decomposition behaviour similar to other organic dusts, with additives altering the activation energy correction factor. Processing additives reduce crystallization enthalpy, apparently decreasing thermal stability compared to purer powders. Fine particles (<50 μm) increase suspension potential, highlighting the need for dust control measures in industry. Elevated Al and Mg content, coupled with higher alkalinity, correlate with higher ignition energies, confirming the presence of such metal ions in the form of solid salts which act as ignition suppressors from a flammability point of view. Theoretical MIE values merged all the information collected during the experimental campaign providing reliable values to be used for safety purposes. Moreover, they matched expected experimental ranges, validating the predictive model.
Concluding, the developed methodology can be considered as a useful tool reducing reliance on costly experimental MIE testing, offering a reliable theoretical framework applicable to cocoa and potentially other food powders. For industry, this means safer design of storage and handling systems, with targeted mitigation strategies for powders with low alkalinity and fine particle fractions.

### References

ADM Cocoa, 2006, De Zaan Cocoa Manual, Archer Daniels Midland, Amsterdam.
Amyotte P., Eckhoff R., 2010, Dust explosion causation, prevention and mitigation: An overview, J. Chem. Health Safety, 17(1), 15–28.
Bartknecht W., 1989, Dust Explosions: Course, Prevention, Protection, Springer, Berlin.
Chapman G.M., Akehurst S., Wright B.T., 1971, Crystallization studies of cocoa butter, J. Am. Oil Chem. Soc., 48, 824–830.
Eckhoff R.K., 2003, Dust Explosions in the Process Industries, 3rd ed., Gulf Professional Publishing, Houston.
Fumagalli A., Derudi M., Rota R., Snoeys J., Copelli S., 2017, Prediction of the deflagration index for organic dusts as a function of the mean particle diameter, J. Loss Prev. Process Ind., 50, pp. 67 - 74
Ioannidi E., Böttcher R., Thalmann M., et al., 2021, Thermal properties of cocoa butter and chocolate, Food Struct., 29, 100197.
Scotton M.S., Barozzi M., Derudi M., Rota R., Copelli S., 2020, Kinetic free mathematical model for the prediction of Kst values for organic dusts with arbitrary particle size distribution, J. Loss Prev. Process Ind., 67, 104218.
Taveau J., et al., 2019, Influence of trace metals on dust ignition sensitivity, Process Saf. Prog., 38, e12003.
Wang C., Zhou Q., Liu J., et al., 2021, Effects of metallic elements on the explosibility of organic dusts, Powder Technol., 377, 831–840.
Wille R.L., Lutton E.S., 1966, Polymorphism of cocoa butter, J. Am. Oil Chem. Soc., 43, 491–496.
Zhang L., Liu H., Sun J., 2020, Role of mineral impurities in dust explosions, J. Loss Prev. Process Ind., 65, 104127.