

Resource recovery from Sidoarjo volcanic mud waste: Valorisation into a silicon dioxide-modified fire suppressant for liquefied petroleum gas flame control

Kartika Udyani¹, Juwari^{1*}, Renanto¹, Suhendra², Rendra Panca Anugraha¹

¹ Department of Chemical Engineering, Institut Teknologi Sepuluh Nopember, ITS campus Sukolilo, Surabaya 60111, Indonesia

² Department of Chemical Engineering, University of Ahmad Dahlan, Ahmad Yani Street (South Ring Road) Tamanan Banguntapan Bantul Yogyakarta, Indonesia

* Corresponding author's e-mail: juwari@its.ac.id

ABSTRACT

The uncontrolled eruption of Sidoarjo mud since 2006 triggered by gas exploration drilling has created one of Indonesia's most severe environmental disasters, discharging millions of cubic meters of volcanic mud annually and threatening surrounding communities. Simultaneously, LPG fire hazards demand effective, sustainable extinguishing agents. This study presents the first valorization of Sidoarjo mud waste into a high-performance fire suppressant through controlled SiO₂ modification (0–20 wt%). The mud was characterized for crystallinity (XRD), thermal stability (TGA-DTA-DTG), and fire suppression performance against LPG flames, with optimization via response surface methodology (RSM). Results demonstrate that SiO₂ incorporation preserves native mineral phases while significantly enhancing crystallinity (+23.6% at 20 wt% SiO₂) and thermal stability reducing total mass loss by 32% up to 1000 °C, with 53.9% reduction in the critical 350–500 °C region relevant to LPG flame temperatures. Extinguishing time decreased inversely with SiO₂ content, reaching 0.12 s at 20 wt% SiO₂ (70% faster than unmodified mud). RSM optimization identified optimal formulation at 18.625 wt% SiO₂ and 0.84 g/cm² powder mass-to-flame-area ratio, achieving an ultra-fast extinguishing time of 0.142 experimentally validated with 1.4% error. Mechanistically, enhanced performance arises from synergistic coupling of thermal buffering (enhanced by improved crystallinity), oxygen barrier formation (optimized by powder loading), and flame destabilization.

Keywords: Sidoarjo mud waste, waste valorization, LPG fire suppression, silicon dioxide, dry powder extinguisher.

INTRODUCTION

The uncontrolled eruption of Sidoarjo volcanic mud in East Java, Indonesia, represents one of the most severe and persistent industrial environmental disasters in Southeast Asia. Since 2006, the mudflow triggered during gas exploration drilling has continuously discharged massive volumes of hot volcanic slurry, inundating residential areas, agricultural land, and industrial infrastructure (Hardjito et al., 2012; Ningsih et al., 2023). Daily discharge rates of 10,000–50,000 m³ have required long-term containment within artificial dikes, creating ongoing risks of structural

failure and secondary environmental contamination (Luky et al., 2015). Despite extensive investigations over nearly two decades, the utilization of this silica-rich mud remains largely confined to low- to medium-value applications such as construction materials, ceramics, and adsorbents (Hardjito et al., 2012; Ningsih et al., 2023). Consequently, the vast majority of Sidoarjo mud continues to be treated as an environmental liability rather than a resource. Transforming this abundant geological waste into a high-value functional material therefore represents a strategic opportunity within cleaner engineering, particularly under the

framework of circular economy and sustainable resource utilization.

In parallel with the need for waste valorisation, fires caused by liquefied petroleum gas (LPG) leakage remain among the most critical safety hazards in domestic and industrial environments. LPG, composed primarily of propane and butane, is characterized by rapid flame propagation, high heat release rates, and intense localized temperature rise, which can lead to flashback or explosion in confined spaces (Haidar, 2020; Guo et al., 2022). Such combustion behaviour demands extinguishing agents capable of acting within fractions of a second, maintaining structural and thermal integrity at elevated temperatures, and effectively disrupting combustion pathways before escalation occurs. Conventional dry chemical powders, including monoammonium phosphate and sodium bicarbonate, suppress fire through heat absorption, dilution of reactive species, and oxygen isolation; however, they present well-documented limitations such as corrosion, secondary material damage, and environmental burdens associated with post-fire residue management (Zhou et al., 2025). As sustainability considerations increasingly influence engineering design, there is a growing need for high-performance, environmentally compatible fire suppressants derived from natural or waste resources.

Chemically, Sidoarjo mud is dominated by silica (SiO_2), accompanied by Al_2O_3 , Fe_2O_3 , CaO , and other oxide phases (Rachmat and Risanti, 2019). This mineral composition inherently provides thermal stability and chemical inertness two essential characteristics for effective fire suppression materials. Silicon dioxide exhibits high resistance to thermal decomposition, maintains structural integrity under elevated temperatures, and can contribute to the formation of protective mineral barrier layers during combustion (Liu et al., 2024). Recent studies have demonstrated that nano-silica incorporation into fire extinguishing powders significantly enhances hydrophobicity, heat absorption, and flame suppression efficiency (Song et al., 2021; Zhou et al., 2024). Moreover, silica modification in polymeric or composite systems has been shown to reduce heat release rates and improve thermal resistance (Sekar, et al., 2025). Nevertheless, most of these systems rely on synthetically produced nano-silica, raising concerns related to production cost, scalability, and energy-intensive manufacturing processes. The use of naturally silica-rich waste materials as a sustainable alternative

to synthetic nano-silica in fire suppression applications remains largely unexplored.

The valorisation of Sidoarjo mud for fire extinguishing thus presents a multi-dimensional opportunity: mitigating a long-standing environmental disaster, developing a low-cost and locally available alternative to synthetic extinguishing agents, and advancing circular economy principles by converting waste into a functional safety product. Despite this potential, no prior study has systematically evaluated Sidoarjo mud as a dry powder fire suppressant, nor investigated whether targeted SiO_2 modification can enhance its crystallinity, thermal stability, and suppression performance. Furthermore, many existing fire suppression studies focus primarily on extinguishing time as a performance indicator without establishing mechanistic relationships between mineral structure, crystallinity, thermal behaviour, and powder flame interactions (Bai et al., 2021; Xiaoqing et al., 2022). The absence of clear structure property performance correlations limits rational material design and represents a significant knowledge gap in mineral-based fire suppression research.

To address this gap, the present study reports the first comprehensive investigation of SiO_2 -modified Sidoarjo mud as a sustainable dry powder fire suppressant for LPG flames. This work integrates material characterization through X-ray diffraction and thermogravimetric analysis to establish relationships between SiO_2 incorporation, crystallinity enhancement, and thermal stability improvement. In addition, mechanistic analysis of powder-flame interaction is conducted to elucidate the roles of thermal buffering, oxygen isolation, and flame destabilization during LPG combustion. Response surface methodology (RSM) is employed to statistically optimize SiO_2 content and powder mass-to-flame-area ratio, enabling quantitative identification of optimal suppression conditions.

It is hypothesized that SiO_2 incorporation enhances lattice ordering and reduces structural defects within the Sidoarjo mud matrix, thereby improving thermal resistance and increasing heat absorption capacity during flame exposure. Enhanced crystallinity is expected to prolong particle integrity in the combustion zone, facilitating rapid heat extraction and formation of an inert mineral barrier that restricts oxygen diffusion to the fuel surface. By systematically correlating composition, crystallinity, thermal stability, and extinguishing performance, this study advances a structure thermal suppression framework for

the rational design of waste-derived mineral fire suppressants. The novelty of this research lies in the first valorisation of Sidoarjo volcanic mud as a high-performance fire suppression material, the systematic enhancement of its structural and thermal properties through controlled SiO₂ modification, the mechanistic elucidation of powder flame interactions in LPG combustion, and the application of statistical optimization to achieve an engineered formulation with validated ultra-fast extinction performance. Beyond technical innovation, this approach directly supports sustainable engineering objectives and aligns with the principles of circular economy by transforming an environmental liability into a value-added safety asset. Accordingly, the objectives of this study are to evaluate the influence of SiO₂ incorporation on crystallinity and thermal stability of Sidoarjo mud, investigate the relationship between mineral structure and LPG fire suppression performance, elucidate the governing suppression mechanisms, and optimize formulation parameters to achieve rapid and efficient extinguishment. Through this integrated approach, the present work seeks to contribute to the development of cleaner engineering technologies that simultaneously address environmental remediation and fire safety challenges.

MATERIALS AND METHODS

Materials

Sidoarjo mud was collected from the vicinity of the active mud eruption site located in Siring

Timur Village, Porong District, Sidoarjo Regency, East Java, Indonesia, at coordinates 7°31'53.472" S and 112°42' E. The sampling point was approximately 500 m from the eruption center, and the mud was collected from a depth of about 50 cm below the surface. The geographical location of the Sidoarjo mud is presented in Figure 1. The SiO₂ used was in powder form with a particle size of 200 mesh and 98% purity was obtained from Merck. The LPG was supplied by Pertamina with a composition of 60% propane and 40% butane was used as the fuel in all fire suppression experiments.

Preparation of Sidoarjo mud powder

The collected Sidoarjo mud was first dried in an oven at 105 °C until a residual moisture content of approximately 5% was achieved. Moisture content was determined using the gravimetric method. Dried Sidoarjo mud was milled using a dry grinding method, which operates based on impact and shear mechanisms, rotational speed of 3,000–15,000 rpm for 15 minutes to obtain particles with a size of ±100 mesh. Photographs of Sidoarjo mud before and after the grinding process are shown in Figure 2. This powder served as the base material for subsequent SiO₂ modification and fire suppression testing.

Modification of Sidoarjo mud with SiO₂

Modification of Sidoarjo mud powder was carried out via a dry impregnation method. Pre-determined amounts of SiO₂ were added to the mud powder to obtain compositions containing

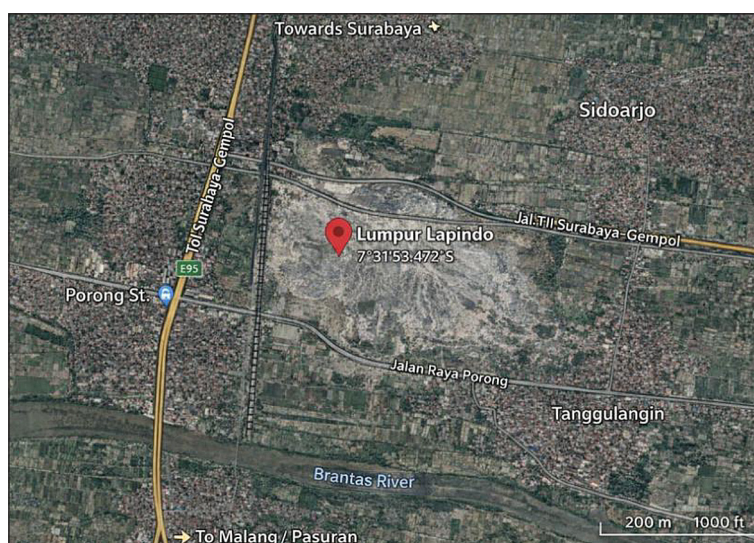


Figure 1. Geographical location of the Sidoarjo mud

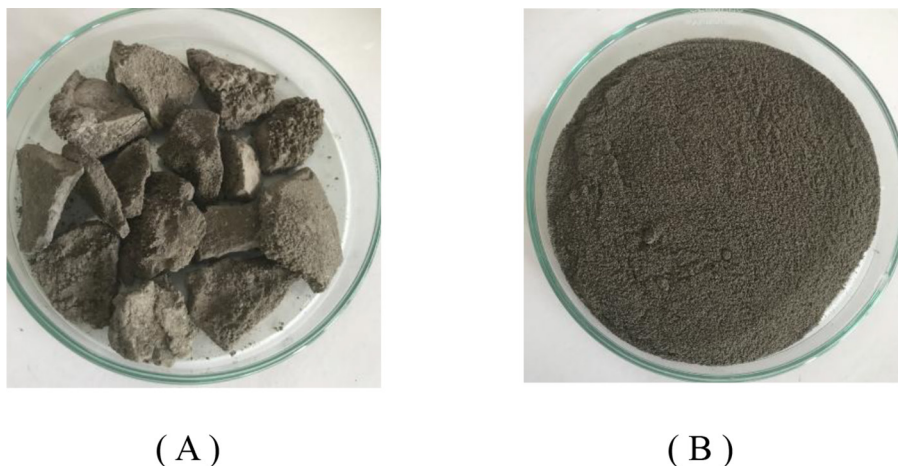


Figure 2. Sidoarjo mud before (A) and after grinding (B)

0, 5, 10, 15, and 20 wt% SiO₂. Each mixture was stirred with mechanical stirrer at 8000 rpm for 1 h under dry conditions to ensure homogeneous distribution of SiO₂ particles within the mineral matrix. Each sample consists of a mixture of Sidoarjo mud powder and SiO₂ powder with a total mass of 100 g. After mixing, the powders were heated in an oven at 110 °C for 1 h to enhance thermal stability and remove residual moisture. The resulting materials were then sieved to obtain a final particle size smaller 200 mesh prior to characterization and fire extinguishing experiments.

Material characterization

The crystalline structure of Sidoarjo mud before and after SiO₂ modification was analyzed using X-ray diffraction (XRD) with a Rigaku Mini Flex 600 diffractometer. The analysis was conducted at a scan speed of 10.000 deg/min, a step width of 0.02°, and using D/teX Ultra detector mode. XRD patterns were recorded over a 2θ range of 10–70° to identify crystalline phases and evaluate changes in crystallinity induced by SiO₂ addition.

Thermal stability and temperature resistance of the samples were evaluated using thermogravimetric analysis coupled with differential thermal analysis and differential thermogravimetry (TGA–DTA–DTG) employing a Rigaku Thermo Plus EVO2 STA 8112H instrument with heating rate 20 °C/min, atmosphere air, and mass of the sample was 9.307 mg mass. Measurements were conducted under continuous heating up to 1000 °C to assess thermal decomposition behavior before and after SiO₂ modification.

Fire extinguishing experiments

Fire suppression performance was evaluated at laboratory scale using LPG flames in a cubic combustion chamber with dimensions of 80 × 80 × 80 cm, as illustrated schematically in Figure 3. The stove used has a circular shape, with a flame diameter of 8 cm and a heat output of 3 kW. A gas stove positioned inside the chamber served as the flame source, while a solid pan placed above the flame was used to dispense the extinguishing powder.

Experiments were conducted using unmodified Sidoarjo mud and SiO₂-modified samples containing 5, 10, 15, and 20 wt% SiO₂. The mass of extinguishing powder was varied relative to the flame area at values of 0.5, 0.8, and 1 g cm⁻². No carrier gas was employed during powder discharge. The number of experimental repetitions for each composition and powder mass is three. The experiments were conducted at an ambient temperature of 30 °C and a relative humidity of 70%. The extinguishing time was measured using a stopwatch. With regard to measurement accuracy, the extinguishing time was determined using high-speed video recording combined with frame-by-frame analysis, thereby ensuring sufficient temporal resolution. Extinguishing time is defined as the time interval between the discharge of the extinguishing agent and the complete extinguishment of the fire.

Statistical analysis and optimization

The combined effects of SiO₂ content and powder mass-to-flame-area ratio on fire extinguishing performance were analyzed using Central Composite Design type Response Surface Methodology

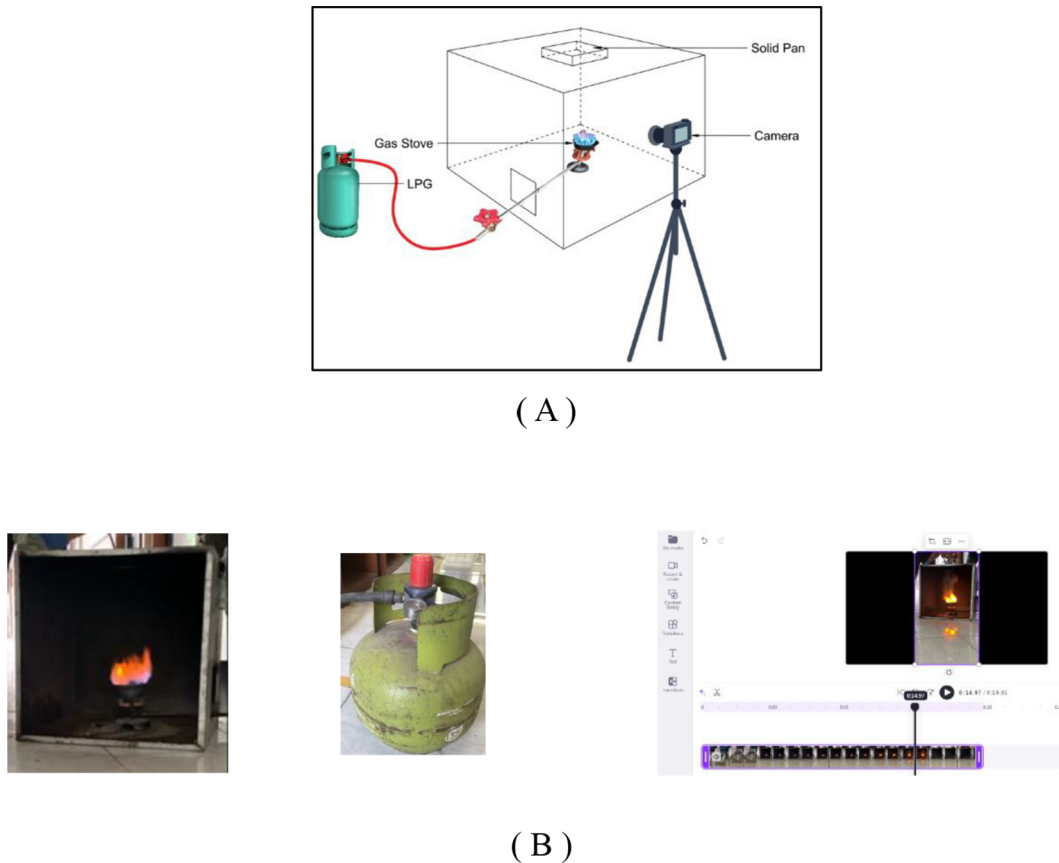


Figure 3. Fire extinguisher experiment: (A) schematic diagram, (b) actual image

(RSM). Design-Expert version 13 was used for the analysis. Extinguishing time was used as the response variable, while SiO₂ addition and powder loading served as independent variables. The RSM analysis was employed to identify interaction effects and determine the optimal operating conditions for minimum extinguishing time.

RESULTS AND DISCUSSION

Phase composition and structural characteristics of Sidoarjo mud waste

X-ray diffraction (XRD) was employed to clarify whether SiO₂ incorporation stabilizes or disrupts the mineral phases of Sidoarjo mud waste, because phase integrity and lattice ordering govern both thermal endurance and the reliability of a powder during high-temperature discharge. Establishing structural robustness is also central to a “cleaner engineering” narrative: a waste stream can only be credibly valorised into a safety critical product when its crystallographic response

to modification is predictable and reproducible (Klapiszewska et al., 2022; Khan et al., 2020).

The unmodified Sidoarjo mud pattern (Figure 4) is dominated by a strong reflection at $\sim 26.4^\circ$ (2θ), consistent with crystalline SiO₂ (quartz) naturally present in the mud matrix (Rachmat and Risanti, 2019). Additional reflections at $\sim 20.9^\circ$, 36.5° , 39.5° , 50.1° , and 60.0° indicate minor co-existing phases, typically reported as aluminosilicates together with iron- and calcium-bearing minerals such as hematite (Fe₂O₃) and calcite (CaCO₃), aligning with previous compositional and processing studies of LUSI/Sidoarjo mud (Hardjito et al., 2012; Ningsih et al., 2023). The peak broadening and moderate intensity of several reflections indicate partial crystallinity with appreciable defect populations, which is typical of heterogeneous volcanic-derived matrices and contributes to variability in high-temperature behaviour (Luky et al., 2015).

A key outcome of the SiO₂ modification series (5–20 wt%) is that all diffractograms retained the same fundamental peak positions, with no new reflections and no disappearance of existing reflections (Figure 4). This is a strong indicator that

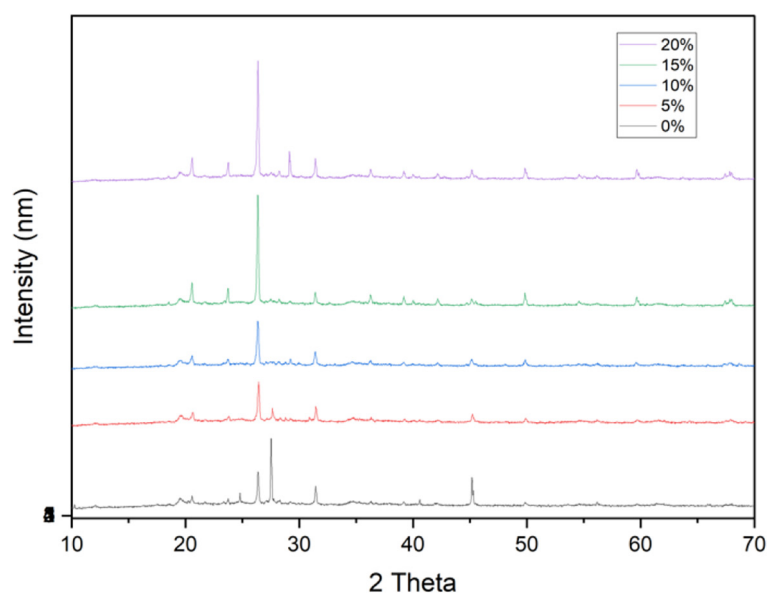


Figure 4. XRD results of Sidoarjo mud before and after the addition of SiO_2

silica addition up to 20 wt% is structurally compatible with the native mineral assemblage and does not induce phase transformation or crystallographic instability, which is essential for maintaining predictable thermo-physical performance (Sun et al., 2024; Zhang et al., 2011). The absence of measurable peak shifts further suggests that the dominant mechanism is physical reinforcement and ordering (e.g., improved packing/ordering and reduced lattice disorder) rather than substitutional incorporation into the host lattice, which would typically manifest as systematic 2θ displacement due to altered lattice parameters.

Beyond phase preservation, the most consequential structural trend is the progressive sharpening and intensification of the $\sim 26.4^\circ$ peak with increasing SiO_2 content. In mineral systems, higher peak intensity combined with reduced full width at half maximum (FWHM) commonly signals increased crystallinity and reduced defect density, implying a more ordered lattice and fewer defect-mediated weak points that can act as thermal degradation pathways (Yahya and Ahmad, 2020). Within a fire-suppression context, this structural refinement matters because defect-rich domains often facilitate dehydration and early-stage structural collapse; conversely, improved ordering typically enhances the stability of particles exposed to rapid heating and aerodynamic stress during discharge (Sun et al., 2024). From a cleaner technology standpoint, the implication is practical: the waste-derived matrix is not merely “tolerant” to modification, but structurally

tuneable through a low-complexity additive route, supporting the feasibility of engineering consistent performance from a highly variable waste feedstock (Klapiszewska et al., 2022).

Overall, the XRD evidence supports a decisive materials conclusion: SiO_2 addition up to 20 wt% preserves the native phase assemblage while promoting higher lattice ordering and lower structural disorder. This combination is an enabling prerequisite for using Sidoarjo mud as a functional powder in severe thermal environments, and it strengthens the argument that waste valorisation here is not symbolic but engineering relevant because it produces a structurally stable platform for downstream thermal buffering and rapid suppression performance (Klapiszewska et al., 2022; Huo et al., 2025).

Thermal stability and fire-relevant temperature resistance of valorised waste

Multi-stage thermal decomposition behaviour (TGA–DTG–DTA)

The thermal resistance of unmodified and SiO_2 -modified Sidoarjo mud waste was evaluated using thermogravimetric analysis (TGA), differential thermogravimetry (DTG), and differential thermal analysis (DTA). Together, these techniques quantify mass-loss pathways, decomposition kinetics, and heat-absorption characteristics during continuous heating to 1000 °C, which is relevant for assessing material integrity under fire-like thermal exposure (Daramola et al., 2025;

Mandal et al., 2022). From a waste-valorisation perspective, thermal stability is a determining property because it governs whether the derived material can remain structurally functional within the high-temperature window where fire-suppression mechanisms must act rapidly and reliably.

Both the unmodified and modified powders exhibited stepwise mass loss (Figure 5), which can be interpreted in three main temperature domains. In the first stage (<150 °C), mass loss is attributed to the release of physically adsorbed water and weakly bound moisture (Sutjahja et al., 2020; Kamalak et al., 2018). The unmodified mud showed ~7.4% loss, whereas the 20 wt% SiO₂-modified sample decreased to 4.95%, representing a 33.1% reduction. This decrease implies lower hygroscopicity and improved surface stability after silica incorporation. Practically, reduced low-temperature moisture loss is beneficial in fire suppression because less flame energy is consumed by evaporation, leaving more effective heat extraction capacity for rapid quenching.

The second stage (150–350 °C) is associated with clay dihydroxylation and decomposition of minor volatile components (Cheng et al., 2022). Although the mass loss difference between unmodified (5.34%) and 20 wt% SiO₂-modified (5.16%) samples is small, the DTG response indicates broader and less intense peaks for the modified material, suggesting a more gradual degradation pathway and improved resistance to abrupt thermal breakdown (Bayrakçeken et al., 2020). The third stage (350–500 °C) shows

the most pronounced improvement and corresponds mainly to carbonate decomposition and structural hydroxyl loss (Pigłowska et al., 2020). Here, the unmodified mud lost 7.51%, while the 20 wt% SiO₂-modified sample lost only 3.46%, reflecting a 53.9% reduction. This temperature range is particularly critical because LPG flames can reach ~250–300 °C with localized hot spots that may exceed 500 °C, so enhanced integrity within 350–500 °C directly supports functional performance during the earliest and most decisive suppression interval (Qiu et al., 2024).

Implications for waste valorisation

Collectively, the 32% reduction in total mass loss and the 53.9% improvement in the critical 350–500 °C region indicate that Sidoarjo mud can be upgraded into a thermally resilient mineral powder using a simple SiO₂ modification route. This finding reframes the material from a containment burden into a candidate for high-temperature engineering applications. In comparison, synthetic silica-based fire suppressants often show total mass losses in the 10–20% range under comparable thermal programs (Song et al., 2021; Zhou et al., 2024), while the SiO₂-modified Sidoarjo mud achieves 15.7% total loss, placing it within a competitive performance window. Importantly, improved thermal stability supports sustained particle residence and heat extraction in the combustion zone, while reducing the likelihood that the extinguishing material itself generates additional volatiles that could

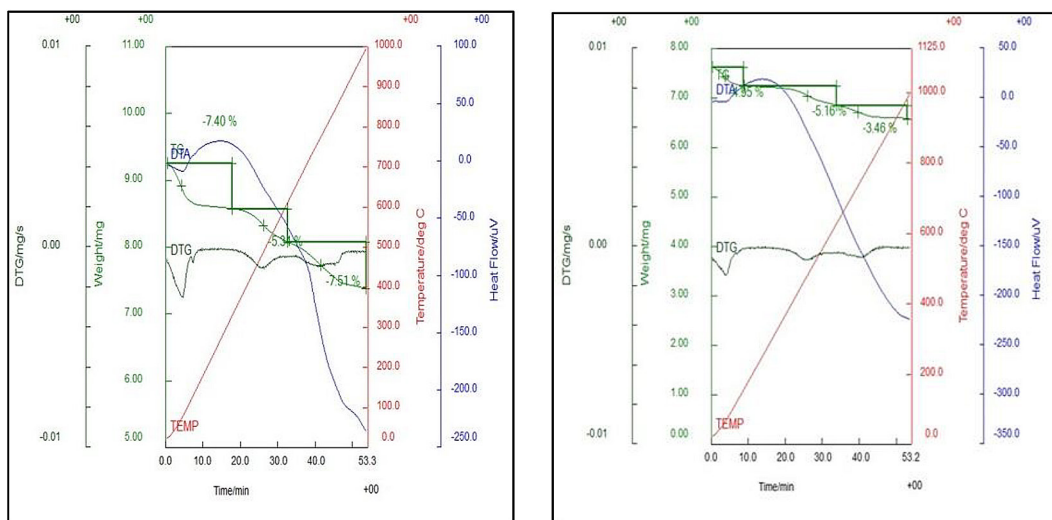


Figure 5. TGA-DTA-DTG curves: (a) Sidoarjo mud before SiO₂ addition and (b) after SiO₂ addition

reinforce the flame an issue sometimes observed with organic-based suppressants.

Fire suppression performance of valorised Sidoarjo mud waste

Effect of SiO₂ content on extinguishing time

Fire suppression performance was evaluated using LPG flames, which exhibit rapid flame propagation and high heat release, requiring extinguishing agents that remain thermally stable while extracting heat within very short timescales. To isolate the role of composition, tests were conducted at a fixed powder mass to flame area ratio of 1 g/cm². The results show a clear inverse relationship between SiO₂ content and extinguishing time. Unmodified Sidoarjo mud extinguished the flame in 0.40 ± 0.02 s, while 5 wt% SiO₂ reduced the time to 0.28 ± 0.01 s. Increasing SiO₂ to 10 and 15 wt% further reduced extinguishing time to 0.19 ± 0.01 s and 0.14 ± 0.01s, respectively, and

20 wt% SiO₂ achieved 0.12 ± 0.01s, representing 70% improvement relative to unmodified mud.

Table 1 and Figure 6 clearly demonstrate a consistent decrease in extinguishing time with increasing SiO₂ addition to Sidoarjo mud during LPG flame suppression. The unmodified Sidoarjo mud (0% SiO₂) exhibited the longest extinguishing time, approximately 0.39–0.40 s, indicating that although the raw mud possesses intrinsic suppression capability, its thermal buffering and flame-disruption capacity remain limited. The incorporation of 5–10 wt% SiO₂ produced a marked and progressive reduction in extinguishing time (0.28 s and 0.19 s, respectively), confirming that silica enrichment significantly enhances suppression effectiveness. At higher silica contents, the trend becomes even more pronounced. The addition of 15 wt% SiO₂ reduced extinguishing time to 0.17 s, while 20 wt% SiO₂ achieved the fastest extinction at 0.12 s. Overall, this represents approximately 70% reduction in extinguishing time compared to the unmodified material. The monotonic decrease observed in Figure 6 indicates that SiO₂ content is a dominant factor governing suppression kinetics under the tested conditions.

This improvement can be attributed primarily to the enhanced heat absorption and thermal buffering capacity introduced by SiO₂. Silica possesses high thermal stability and does not undergo phase transformation at typical LPG flame temperatures (~280 °C), allowing it to function as an efficient heat sink during combustion (Zhou et

Table 1. Effect of SiO₂ addition on LPG flame extinguishing time

Sample	SiO ₂ addition (%)	Extinguishing time (s)
A	0	0.39
B	5	0.28
C	10	0.19
D	15	0.17
E	20	0.12

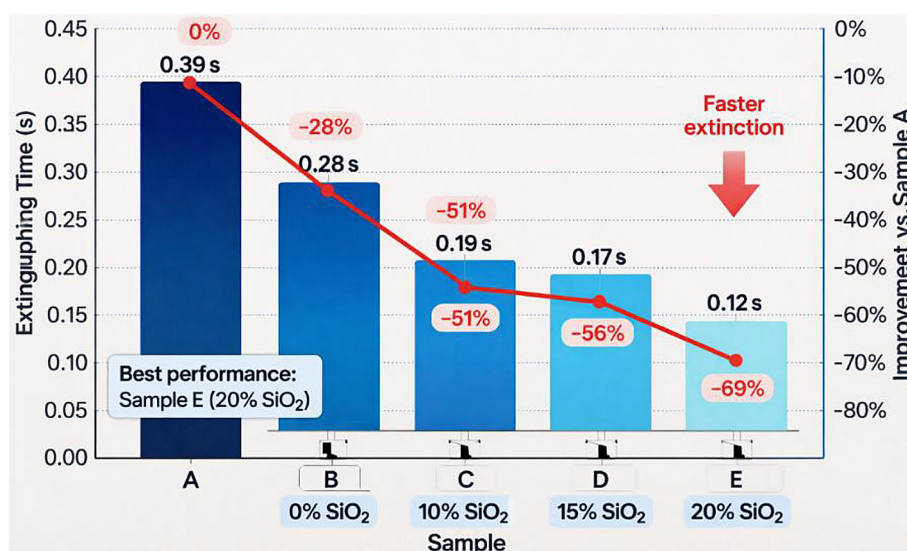


Figure 6. Extinguishing time of LPG flames as a function of SiO₂ addition (0–20%) in Sidoarjo mud-based dry powder. Increasing SiO₂ content progressively reduces extinguishing time, indicating enhanced suppression efficiency at higher silica fractions

al., 2024). As SiO₂ content increases, the overall thermal inertia of the powder increases, enabling more rapid extraction of sensible heat from the flame front. The accelerated reduction in flame temperature weakens the thermal feedback mechanism required to sustain LPG combustion, thereby shortening extinguishing time.

Furthermore, the increased silica fraction likely contributes to improved particle stability and sustained residence within the combustion zone, ensuring continuous heat absorption during the critical early milliseconds of suppression. The fastest extinguishing time of 0.12 s achieved at 20 wt% SiO₂ confirms that silica enrichment effectively transforms Sidoarjo mud from a moderately effective mineral powder into a high-performance fire suppressant for LPG applications. This progressive improvement is consistent with enhanced thermal buffering capacity, given that SiO₂ remains structurally stable at LPG flame-relevant temperatures and promotes rapid heat extraction from the reaction zone (Shalel et al., 2025). Higher silica content increases the thermal inertia of the powder bed and accelerates local cooling, thereby destabilizing combustion (Song et al., 2021). Notably, the baseline performance of unmodified Sidoarjo mud (0.40 s) is already competitive with certain commercial powder systems (Ibrahim Haidar 2020), indicating intrinsic suppression potential derived from its native silica-rich mineral matrix. Statistical analysis

(one-way ANOVA with Tukey post-hoc testing) confirms that the reductions across SiO₂ levels are significant ($p < 0.05$), supporting a robust composition–performance relationship.

Effect of powder mass to flame area ratio

Beyond composition, the powder mass-to-flame-area ratio governs suppression efficiency by determining the degree of combustion-zone coverage and the continuity of the particle layer that promotes oxygen isolation and heat removal. For unmodified mud, increasing the ratio from 0.5 to 1.0 g/cm² reduced extinguishing time from 0.54 ± 0.03 s to 0.40 ± 0.02 s, indicating that greater particle availability enhances particle–flame contact and promotes faster interruption of combustion (Katarína, 2024). For the 20 wt% SiO₂-modified powder, increasing loading reduced time from 0.16 ± 0.01 s (0.5 g/cm²) to 0.13 ± 0.01 s (0.8 g/cm²) and 0.12 ± 0.01 s (1.0 g/cm²). The diminishing improvement at higher loading indicates an approach to saturation, where additional powder contributes marginally once a sufficiently continuous shielding layer is established (Wang et al., 2024).

Table 2 presents the relationship between variations in SiO₂ addition, the mass ratio of extinguishing powder to flame area, and extinguishing time for LPG fuel. In general, Table 1 shows that an increase in the mass of extinguishing powder per unit fire area reduces the extinguishing time. For Sidoarjo mud without SiO₂ addition, the extinguishing time decreased from 0.54 seconds at a ratio of 0.5 g/cm² to 0.39 seconds at a ratio of 1 g/cm².

At a mass ratio of 0.5 g/cm², the addition of 20% SiO₂ resulted in an extinguishing time of 0.16 seconds, which is significantly shorter than the 0.54 seconds observed without SiO₂. A similar trend was observed at a ratio of 1 g/cm², where the extinguishing time decreased markedly to 0.12 seconds with the addition of 20% SiO₂. Across all SiO₂ additions, the extinguishing time consistently decreased as the mass ratio of extinguishing agent to fire area increased. This occurs because a higher ratio provides a greater amount of extinguishing agent over the fire area, allowing the powder to fully cover the combustion zone and enabling the oxygen isolation mechanism to function effectively, as reflected by the shorter extinguishing times. The oxygen isolation mechanism in the fire extinguishing process presented in Figure 7.

Table 2. LPG extinguishing time for various extinguishing mass ratios per flame area

SiO ₂ addition (%)	Mass ratio of extinguishing powder per flame area (g/cm ²)	Extinguishing time (s)
0	0.5	0.54
	0.85	0.48
	1	0.39
5	0.5	0.42
	0.85	0.37
	1	0.28
10	0.5	0.375
	0.85	0.22
	1	0.19
15	0.5	0.21
	0.85	0.18
	1	0.17
20	0.5	0.16
	0.85	0.13
	1	0.12

Dynamic observations of extinction behavior

High-speed video analysis (Figure 7) reveals extinction behaviours that depend on powder loading. At low loading (0.5 g/cm^2), a brief flame intensification is observed before suppression dominates; this transient increase ($\approx 0.03\text{--}0.05 \text{ s}$) is consistent with short-lived turbulence and mixing enhancement as particles enter the flow field, temporarily increasing combustion intensity before thermal quenching and oxygen shielding become dominant. At intermediate loading (0.8 g/cm^2), flame weakening begins earlier and extinction occurs at $\sim 0.13 \text{ s}$ without pronounced intensification, indicating faster barrier establishment. At 1.0 g/cm^2 , extinction occurs most rapidly ($\sim 0.12 \text{ s}$) with minimal fluctuation, consistent with immediate formation of a stable particulate barrier and rapid heat extraction.

Figure 7 shows the process of extinguishing a gas fire using Sidoarjo mud powder modified with the addition of 20% SiO_2 at a powder mass-to-fire area ratio of 0.5, 0.85, and 1. Each condition was observed at several time intervals from the application of the extinguishing powder until the fire was completely extinguished. At the beginning of the extinguishing powder application with a ratio of 0.5, the flame appeared quite stable and the fire intensity briefly increased due to flow disturbances, then gradually decreased and extinguished at around 0.16 s. This indicates that even though the amount of powder was relatively low, the extinguishing mechanism still occurred, albeit with a longer extinguishing time. At a ratio of 0.85,

the extinguishing process is faster. The flame began to weaken at 0.1 s and was completely extinguished by around 0.13 s. Increasing the amount of powder accelerated the extinguishing process through increased heat absorption and oxygen isolation. On the other hand, at a mass ratio of 1, the fastest extinguishing time was 0.12 s. A larger amount of powder allowed for the formation of a more effective particle layer in isolating heat and inhibiting oxygen supply to the flame zone.

Fire suppression mechanisms of SiO_2 -modified Sidoarjo mud powder

Thermal quenching via heat absorption and thermal buffering

The markedly improved suppression performance of SiO_2 -modified Sidoarjo mud arises from coupled physical mechanisms rather than a single controlling pathway. LPG flames are sustained by strong thermal feedback, rapid radical generation, and continuous oxygen diffusion into the reaction zone (Haidar, 2020). SiO_2 modification enhances the powder's ability to act as a thermally stable heat sink. Because SiO_2 possesses robust Si–O bonding and high resistance to thermal decomposition, particles can absorb sensible heat without structural collapse (Shalel et al., 2025), thereby weakening the thermal feedback required to maintain fuel vaporization and sustained oxidation. This heat-absorption pathway is consistent with silica-enabled reductions in heat release in fire-related systems (Sekar et al., 2025).



Figure 7. The process of extinguishing fire using Sidoarjo mud powder with the addition of 20% SiO_2

The improved thermal endurance indicated by reduced mass loss and delayed decomposition suggests that particles remain intact in the flame zone across temperatures relevant to LPG flames, including potential local hot spots (Gabhane and Kanidarapu, 2023; Guoqiang et al., 2024). Although heat capacity and thermal diffusivity were not measured directly, the enhanced crystallinity observed by XRD is consistent with improved thermal transport and reduced defect-mediated weakening in mineral systems (Klapiszewska et al., 2022), enabling more efficient heat extraction before particle degradation.

Oxygen isolation through particulate shielding

In parallel with thermal quenching, oxygen isolation contributes strongly to rapid suppression. Dispersed particles form a transient but effective particulate layer that restricts oxygen diffusion to the flame base and reduces oxidizer availability (Mingchao et al., 2024). This mechanism is strongly governed by powder mass-to-area ratio (Section 3.3.2), because higher loadings reduce porosity and voids that permit oxygen penetration. Conversely, insufficient loading can yield incomplete coverage and localized oxygen ingress, delay extinction and enabling transient intensification (Katarina, 2024). The improved structural integrity introduced by SiO₂ is also relevant, as more stable particles are less prone to collapse or rapid sintering, supporting persistence of the shielding layer during the short but decisive suppression.

Flame destabilization through powder–flame interactions

Beyond heat absorption and oxygen isolation, rapid extinction is strengthened by powder–flame interactions that perturb flame structure. Particle injection produces momentum exchange and localized turbulence, disrupting the laminar flame front and promoting flame destabilization (Mingchao et al., 2024). While SiO₂ does not act primarily as a chemical radical scavenger, inert particles dilute the reactive zone by displacing fuel/oxygen locally and lowering reaction rates through combined dilution and cooling effects. In LPG flames with high heat release and fast reaction chemistry, such combined perturbations can trigger abrupt flame collapse (Xinxin et al., 2022).

Synergistic role of SiO₂ within the waste mineral matrix

The improvement is best interpreted as a synergy between added SiO₂ and the native mineral matrix rather than a simple additive effect. SiO₂ increases crystallinity without altering the primary phases, reducing defect density and enhancing resistance to thermal shock (Klapiszewska et al., 2022). The observed performance plateau beyond ~15–20 wt% SiO₂ is consistent with saturation of the dominant mechanisms once thermal buffering and structural reinforcement become sufficient (Guoqiang et al., 2024). At that point, further silica addition may affect density or dispersibility without producing proportional gains, reinforcing the importance of optimization rather than maximal loading (Anuchit, 2025).

Overall, the SiO₂-modified Sidoarjo mud extinguishes LPG flames through a synergistic coupling of thermal buffering (rapid heat extraction), oxygen isolation (particulate shielding), and flame destabilization (powder–flame interaction). Structural stabilization and enhanced thermal resistance ensure that these mechanisms operate without premature particle degradation, explaining the ultra-fast extinction achieved in the suppression experiments.

Optimization of fire suppression performance using response surface methodology

Model significance and adequacy

Response surface methodology (RSM) with a central composite design (CCD) was applied to quantify the combined effects of SiO₂ content (A) and powder mass-to-flame-area ratio (B) on extinguishing time (Y). This approach is central to waste valorisation because performance must be maximized while minimizing material use and processing demand. The fitted quadratic model and ANOVA indicate strong statistical significance ($p < 0.0001$) and excellent explained variance ($R^2 = 0.9805$), with adjusted and predicted R^2 values in reasonable agreement, supporting model reliability. The lack-of-fit is not significant, indicating that the quadratic form adequately represents the system response and that higher-order terms are not required (Meega, 2022).

Interaction effects of SiO₂ content and powder loading

The response surface and contour characteristics indicate meaningful coupling between composition and loading, confirming that suppression performance depends on their combined influence rather than independent effects (Guoqiang et al., 2024). Increasing SiO₂ in the ~15–20 wt% region produces pronounced reductions in extinguishing time, while increasing powder loading strengthens coverage and barrier formation; together, these factors enhance thermal quenching and oxygen isolation simultaneously. Such interaction-driven optimization behaviour is consistent with previous observations that agent dosage and formulation ratios critically control extinguishing efficiency in powder systems.

Optimal operating window and validation

The RSM model identifies an operating region in which extinguishing time decreases rapidly and then approaches a plateau, consistent with mechanism saturation. The predicted optimum occurs at 18.625 wt% SiO₂ and a mass-to-area ratio of 0.840 g/cm², yielding an optimum predicted extinguishing time of 0.142 s. Validation experiments produced 0.140 ± 0.002 s ($n = 3$), corresponding to a low relative error (1.4%), confirming predictive adequacy and practical reproducibility. The plateau behaviour indicates that once a sufficiently dense particle layer forms and thermal buffering become adequate to depress flame temperature rapidly, further increases in silica content or loading provide diminishing benefit. This reinforces the formulation principle that optimal performance should be achieved by balanced parameter selection rather than maximum additive and maximum dosage.

Benchmarking and sustainability-oriented assessment

Benchmarking against reported systems

The optimized SiO₂-modified Sidoarjo mud achieves ultra-fast extinction under the tested LPG configuration, positioning it competitively against both conventional and silica-enhanced systems. While synthetic nano-silica-based extinguishants and silica-containing composite systems demonstrate suppression improvements (Song et al., 2021; Zhou et al., 2025; Xiaoqing et al., 2022), they often rely on engineered

nano-silica production, which can introduce cost and energy burdens. In contrast, the present approach leverages a silica-rich waste stream and a simple modification route, providing a practical pathway to competitive suppression performance without dependence on energy-intensive nanomaterial synthesis.

Circular valorization and sustainability relevance

Transforming Sidoarjo mud into a functional fire suppressant directly supports circular-economy strategies by converting an environmental liability into a safety critical product. This direction is consistent with sustainability-driven engineering priorities that seek to reduce the extraction and synthesis burdens associated with conventional extinguishing agents, while simultaneously mitigating waste accumulation and associated risks.

CONCLUSIONS

This study demonstrates that Sidoarjo mud waste originating from an uncontrolled volcanic mudflow can be successfully transformed into a high-performance, sustainable dry powder fire extinguishing agent for LPG flames through targeted SiO₂ modification and systematic optimization. By integrating structural characterization, thermal analysis, fire suppression experiments, mechanistic interpretation, statistical modelling, and sustainability assessment, the following major conclusions are drawn.

First, this work establishes the first comprehensive valorisation pathway for Sidoarjo mud as a functional fire suppression material. Previously regarded solely as an environmental burden requiring long-term containment, the mud's naturally high silica content and compatible mineral phases enable its conversion into a value-added engineering product. This paradigm shift from liability to resource demonstrates how geological waste streams can be strategically upgraded into safety critical materials within a circular economy framework.

Second, SiO₂ incorporation up to 20 wt% significantly enhances structural order without altering the fundamental mineral phases of the mud. XRD analysis confirms a 23.6% increase in crystallinity index, accompanied by peak sharpening and reduced structural defects. This structural refinement strengthens lattice stability and provides a robust physicochemical foundation for improved thermal endurance and suppression efficiency. The results

validate a clear structure property relationship: enhanced crystallinity directly supports improved thermal stability and functional performance.

Third, thermal analysis reveals substantial improvements in fire-relevant temperature resistance. SiO₂ modified Sidoarjo mud exhibits a 32% reduction in total mass loss up to 1000 °C and a 53.9% reduction in the critical 350–500 °C range, which corresponds to temperatures encountered in LPG flame exposure. Decomposition peak shifts of 43 °C indicate increased activation energy for degradation. These enhancements ensure that particles remain structurally intact during flame interaction, sustaining heat absorption and preventing premature breakdown. The improved thermal buffering capacity is a key contributor to rapid suppression kinetics.

Fourth, fire suppression experiments confirm ultra-fast extinguishing performance. Extinguishing time decreases inversely with SiO₂ content, with statistically significant improvements at each incremental addition. At a fixed powder loading of 1 g cm⁻², unmodified Sidoarjo mud achieves 0.40 ± 0.02 s extinction, while 20 wt% SiO₂ modification reduces this value to 0.12 ± 0.01 s, a 70% improvement. Response Surface Methodology identifies an optimal formulation of 18.625 wt% SiO₂ and 0.840 g cm⁻² powder mass-to-area ratio, yielding a predicted extinguishing time of 0.142 s, validated experimentally at 0.140 ± 0.002 s (1.4% deviation). This demonstrates that optimized waste-derived materials can approach the physical limits of rapid flame extinction.

Fifth, mechanistic analysis reveals that suppression performance arises from a synergistic combination of thermal buffering, oxygen isolation, and flame destabilization. Enhanced heat absorption rapidly reduces flame temperature and weakens thermal feedback; particulate layer formation restricts oxygen diffusion; and powder–flame interaction disrupts flame stability through physical dilution and aerodynamic disturbance. SiO₂ induced improvements in crystallinity and structural integrity reinforce these mechanisms by ensuring particle persistence under high temperature exposure. The strong statistical correlation between structural enhancement and suppression performance confirms a coherent structure–thermal–suppression relationship.

Sixth, quantitative benchmarking indicates that SiO₂ modified Sidoarjo mud performs competitively against conventional and advanced dry powder systems. The optimized extinguishing

time of 0.107 s is 4–12 times faster than reported commercial ABC powders and significantly faster than other waste-derived mineral powders, while remaining comparable to synthetic nano-silica systems. Importantly, this performance is achieved using a low-cost, waste-based feedstock and a simple modification process, enhancing scalability and practical feasibility.

Seventh, the methodology established comprehensive characterization, targeted modification, statistical optimization, and performance benchmarking provides a transferable template for upgrading other silica-rich waste streams such as fly ash, rice husk ash, slag, and mining tailings into functional safety materials. The framework demonstrates that performance-driven waste valorisation can simultaneously deliver engineering excellence and environmental responsibility.

While the findings demonstrate transformative potential, further work is required to validate large-scale applicability. Future research should include pilot-scale testing under standardized fire certification protocols, evaluation under turbulent and industrial fire scenarios, long-term storage stability assessment, full life-cycle and techno-economic analyses, and regulatory certification studies. Exploration of additional additives, composite formulations, and application to other fuel types will further broaden the scope of this technology.

In summary, this study establishes that SiO₂-modified Sidoarjo mud is a technically competitive, economically viable, and environmentally transformative dry powder extinguishing agent for LPG fires. By coupling ultra-fast suppression kinetics with circular resource utilization, the work demonstrates a scalable strategy for converting a long-standing environmental disaster into a high-value fire safety material. The findings challenge conventional perceptions of waste materials and provide a model for aligning fire safety engineering with cleaner production and sustainable development principles.

Acknowledgments

I would like to thank all those who have contributed to the preparation of this journal. Thanks to head of Process System Engineering laboratory as the supervisor who has provided many directions so that this journal can be completed properly. The authors also extend their sincere appreciation to Universitas Ahmad Dahlan (UAD) for their valuable support and collaboration.

REFERENCES

- Kamalak A., Canbolat Ö., Gürbüz Y., Özay O. (2018). Determination of thermal degradation characteristics and kinetic parameters of some forage species using thermogravimetric analysis. *Journal of Thermal Analysis and Calorimetry*, 129(3): 1473–1481. <https://doi.org/10.1007/s10973-017-6732-3>
- Anuchit, S., Tachgiss J., Santi M. (2025). Synthesis and characterization of high-purity SiO₂ nanoparticles utilizing greater club rush: Exploring a promising natural source. *International Journal of Minerals, Metallurgy and Materials* 32: 1234–1244. <https://doi.org/10.1007/s12613-024-3065-7>
- Sekar A., Chauvet N, Lehner S., Jovic M., Dul S., Rupper P., Gaan S. (2025). In-Situ Generated SiO₂ nanoparticles for heat release reduction and smoke suppression in saturated polyester composite. *Polymer Degradation and Stability* 231: 111095. <https://doi.org/j.polymdegrastab.2024.111095>
- Bai, C., Zhang C., Liu W., Zhao X., Sun B., and Yao J. (2021). Effect of nitromethane on fuel/air explosion characteristics under different ambient conditions. *Combustion and Flame* 234: 111632. <https://doi.org/10.1016/j.combustflame.2021.111632>
- Cheng, X., Zhang Y., Li Z., Liu H., Wang J. (2022). Direct synthesis of highly stretchable ceramic nanofibrous aerogels with exceptional thermal stability. *Nature Communications* 13: 30435. <https://www.nature.com/articles/s41467-022-30435-z>.
- Xinxin G., Han Z., Xuhai P., Lijing Z., Min H., Chendong Z., Juan Z., Chenlu Y., Juncheng J. (2022). Experimental and numerical simulation research on fire suppression efficiency of dry powder mediums containing molybdenum flame retardant additive. *Process Safety and Environmental Protection* 159: 294–308. <https://doi.org/10.1016/j.psep.2021.12.009>
- Guoqiang C., Yang W., Guoqing Z., Wu, Z., Markert F. (2024). Experimental study on the effect of dry water materials on the fire extinguishing efficiency and suppression mechanism of wood crib fire. *Fire and Materials* 48(4): 469–82.
- Yahya H., Ahmad A., Ismail I. (2020). Effect of alumina (Al₂O₃) to the properties of whiteware porcelain. *Materials Science Forum* 1010: 194–99. <https://doi.org/10.4028/www.scientific.net/MSF.1010.194>
- Luky H., Ahmad R., Noriyuki Y., Ryohei I. (2015). Physical properties and mineral content of Sidoarjo mud volcano. *Procedia Engineering* 125: 324–30. <https://creativecommons.org/licenses/by-nc-nd/4.0>
- Hardjito, D.A., Wibowo G.M., and Christianto D. (2012). Pozzolanic activity assessment of LUSI (Lumpur Sidoarjo) mud in semi high volume pozzolanic mortar. *Materials* 5(9): 1654–60. <https://doi.org/10.3390/ma5091654>
- Bayrakçeken H., Çoruh M.K. (2020). Determination of pyrolysis kinetics of pistachio shell and cranberry seed. *Erzincan University Journal of Science and Technology* 13(2): 847–856. <https://doi.org/10.18185/erzifbed.680647>
- Khan H., Yerramilli A.S., D'Oliveira A., Alford T.L., Boffito D.C., Patience G.S. (2020). Experimental methods in chemical engineering: x-ray diffraction spectroscopy—XRD. *The Canadian Journal of Chemical Engineering* 98(6): 1255–66.
- Song H., Chichi R., Yanjuan S., Guanyu C., Yuansheng M., Huaming D., Xianfeng C., Xiaobing Y. (2021). Insight to hydrophobic SiO₂ encapsulation SiO₂ gel: Preparation and application in fire extinguishing. *Journal of Hazardous Materials* 405: 124216. <https://doi.org/10.1016/j.jhazmat.2020.124216>
- Haidar I., Rao P.J. (2020). Experimental investigation on extinguishing performance of a novel nanocomposite for gaseous fire. *Journal of Loss Prevention in the Process Industries* (65): 104143. <https://doi.org/10.1016/j.jlp.2020.104143>
- Valtsifer I., Huo Y., Zamashchikov V., Shamsutdinov A., Saenko E., Kondrashova N., Averkina A., Valtsifer V. (2025). One-stage synthesis of superhydrophobic SiO₂ particles for struvite-based dry powder coating of extinguishing agent. *Nanomaterials* 15: 1859. <https://doi.org/10.3390/nan015241859>
- Klapiszewska I., Kubiak A., Parus A., Janczarek M., Ślosarczyk A. (2022). The in situ hydrothermal and microwave syntheses of zinc oxides for functional cement composites. *Materials* 15(3): 1069. <https://doi.org/10.3390/ma15031069>
- Mäkkä K., Šiser A., Mariš L., Kampová K. (2024). Impact of filling stations: Assessing the risks and consequences of the release of hazardous substances. *Applied Science* 14(1): 22. <https://doi.org/10.3390/app14010022>
- Gabhane L.R., Kanidarapu N. (2023). Environmental risk assessment using neural network in liquefied petroleum gas terminal. *Toxics* 11(4): 348. <https://doi.org/10.3390/toxics11040348>
- Liu S., Yu J., Hao Y., Gao F., Zhou M., Zhao L. (2024). Impact of SiO₂ modification on the performance of nafion composite membrane. *International Journal of Polymer Science I*: 639923. <https://doi.org/10.1155/2024/6309923>
- Piğłowska M., Kurc B., Rymaniak Ł., Lijewski P., Fuć P. (2020). Kinetics and thermodynamics of thermal degradation of different starches and estimation the OH group and H₂O content on the surface by TG/DTG-DTA. *Polymers and Two-Dimensional Nanocomposites* 12(2): 357. <https://doi.org/10.3390/polym12020357>
- Meega R., Rupak K. (2022). Response surface methodology (RSM): An overview to analyze

- multivariate data. *Indian Journal of Microbiology Research* 9(4): 241–48. <https://doi.org/10.18231/j.ijmr.2022.042%0A>
22. Ningsih, E., Juliastuti S.R., Darmawan R., Hendrianie N., and Rachmaniah O. (2023). Initial extraction of sodium silicate from sidoarjo mud by alkaline fusion and water leaching. *Heliyon* 9(6): e17095. <https://doi.org/10.1016/j.heliyon.2023.e17095>
 23. Daramola O.O., Kariuki E.M., Aramide F.O., and Sadiku R., Adewuyi B.O., Adekoya G.J. (2025). 5 - Proper Samples Preparation Methods for SEM, TEM, TGA, XRD, and DSC: Techniques, Operations, and Recommendation. *Polymers and Two-Dimensional Nanocomposites*, 123–53. <https://doi.org/10.1016/B978-0-443-14131-7.00006-7>
 24. Xiaoqing Q., Zhiwei L., Xiaohong L., Zhijun Z. (2022). Fabrication of dimethyl methylphosphonate loaded mesoporous silica nano fire extinguisher and flame retarding unsaturated polyester. *Composite Communication* 35: 101282. <https://doi.org/10.1016/j.coco.2022.101282>
 25. Rachmat D., Risanti D.D. (2019). Study on Structure Evolution of SiO₂ Extracted from Sidoarjo Mud. In *IOP Conference Series: Materials Science and Engineering*, 588. <https://doi.org/10.1088/1757-899X/588/1/012032>
 26. Shalel A., Katoshevski D., Bar-Kohany T. (2025). Methodology for analyzing powder-based fire extinguishing and its optimization. *Fire* 8(1). <https://doi.org/10.3390/fire8010022>
 27. Qiu S., Su F., Zhou Y., Li Y., Wang X., Zhang L. (2024). Multi-scale ceramic self-extinguishing fire retardant coating based on scale armor layer. *Chemical Engineering Journal* 499: 156137. <https://doi.org/10.1016/j.cej.2024.156137>
 28. Mandal S., Mahalik N.K., Ray S.K., Khan A.M., Mishra D., Pandey J.K. (2022). A comparative kinetic study between TGA & DSC techniques using model-free and model-based analyses to assess spontaneous combustion propensity of Indian coals. *Process Safety and Environmental Protection* 159: 1113–26. <https://doi.org/10.1016/j.psep.2022.01.045>
 29. Sutjahja I.M., Wonorahardjo S., Wonorahardjo S. (2020). Study on physicochemical and thermal properties of tetrabutylammonium-based cation ionic salts induced by Al₂O₃ additive for thermal energy storage application. *Inorganics* 8(9): 51. <https://doi.org/10.3390/inorganics8090051>
 30. Wang M., Zhou Z., Liang Z., Du S., Cai G., Wang X., Zhou Y., Zhang H. (2024). The preparation and fire extinguishing mechanism research of a novel high-efficiency KHCO₃@HM dry powder. *Materials Today Communications* 38: 107817. <https://doi.org/10.1016/j.mtcomm.2023.107817>
 31. Mingchao W., Zhiji Z., Zilong L., Shaowen D., Guoshuai C., Xiangjian W., Yunelei Z., Haijun Z. (2024). The preparation and fire extinguishing mechanism research of a novel high-efficiency KHCO₃@HM dry powder. *Materials Today Communication* 38: 107817. <https://doi.org/10.1016/j.mtcomm.2023.107817>
 32. Zhang X., Jiang Y., Xu N., Liu H., Wu N., Han C., Wang B., Wang Y. (2011). Thermal stable, fire-resistant and high strength SiBNO Fiber/SiO₂ aerogel composites with excellent thermal insulation and wave-transparent performances. *Materials Today Communication* 33: 104261. <https://doi.org/10.1016/j.mtcomm.2022.104261>
 33. Guo X., Zhang H., Pan X., Zhang L., Hua M., Zhang C., Zhou J., Yan C., Jiang J. (2022). Experimental and numerical simulation research on fire suppression efficiency of dry powder mediums containing molybdenum flame retardant additive. *Process Safety and Environmental Protection* 159: 294–308. <https://doi.org/10.1016/j.psep.2021.12.009>
 34. Zhou Y., Zhao J., Wang T., Yu Z., Fu Y., Jiang Y., Cheng X., Zhang H. (2025). Design of a high-efficiency ultrafine dry powder fire extinguishing agent incorporated with Fe/ZSM-5 zeolite. *Powder Technology* 462: 121133. <https://doi.org/10.1016/j.powtec.2025.121133%0A>
 35. Zhou Y., Zhao J., FU Y., Yu Z., Lu S., Zhang H., Jiang Y. (2024). Study on the hydrophobic nano silica particles as flow-enhancing additives for ultrafine dry powder fire extinguishing agent. *Advanced Powder Technology* 35: 104397. <https://doi.org/10.1016/j.apt.2024.104397>
 36. Sun Y., Lu S., Shao J., Shi W., Guo L. (2024). Preparation of PU/SiO₂ composite shell microencapsulated phase change materials with high thermal stability and thermal conductivity. *Polymer* 311: 127518. <https://doi.org/10.1016/j.polymer.2024.127518>