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Suppressing underground peat fire and smoldering spread via water, ice, dry ice, and liquid nitrogen

Yichao Zhang [a], Yuying Chen [a], Yunzhu Qin [a], Yizhou Li [a], Yuxin Zhou [a], Zifan Zhang [a], Yuting Jiang [a], Shaorun Lin [a,*], Xinyan Huang [a,b,**]

[a] *Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong*
[b] *State Key Laboratory of Climate Resilience for Coastal Cities, The Hong Kong Polytechnic University, Hong Kong*

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ABSTRACT

Smoldering peat fires are a persistent and globally significant environmental hazard, releasing substantial greenhouse gases and driving long-term ecosystem degradation. Conventional suppression methods, particularly water application, often fail to fully extinguish smoldering fronts due to limited cooling persistence and uneven infiltration within porous peat layers. In this study, we experimentally evaluated the suppression performance of four extinguishing agents (dry ice, ice, liquid nitrogen, and water) under controlled laboratory conditions across a wide range of peat moisture contents (up to 100%). Suppression performance was assessed using three metrics: extinguishment probability, required quantity, and effective cooling duration. We found that dry ice achieved the highest extinguishment probability through sustained sublimation and oxygen displacement, requiring a minimum mass of 41 kg/m^2 for air-dried peat (MC~10%) while providing the longest effective cooling duration (up to 175 min) under current experimental conditions. Liquid nitrogen exhibited rapid and intense cooling, instantaneously reducing soil temperature to around −175 °C; however, its short residence time frequently resulted in rapid temperature rebound. Ice exhibited moderate suppression performance, whereas water required approximately 90 kg/m^2 for air-dried peat (more than twice the mass of dry ice) to achieve comparable suppression. Even in unsuccessful cases, solid suppressants, especially dry ice, slowed fire spread more effectively than liquids by maintaining subcritical fuel temperatures for extended periods. These findings provide new insights into the selection of suppression agents for smoldering peat fires, informing more effective and environmentally conscious fire management strategies for peatland ecosystems.

1. Introduction

Peat is a highly porous, carbon-rich organic material formed through the incomplete decomposition of plant matter under prolonged waterlogged and oxygen-deficient conditions [1–3]. Although peatlands occupy only ~3% of the Earth's terrestrial surface, they are geographically widespread across Southeast Asia, the Americas, and boreal and subarctic regions [4,5]. Critically, these ecosystems store approximately one-quarter of the global soil carbon, making them one of the most significant terrestrial carbon reservoirs [6]. In their undisturbed state, peatlands retain high moisture content, which inhibits combustion and facilitates long-term carbon sequestration [7–9]. However, climate change and human interventions such as drainage for agriculture, deforestation, and land conversion have led to extensive peatland drying, thereby increasing their vulnerability to fire ignition and propagation [10,11]. Once ignited, desiccated peat can release vast quantities of carbon dioxide and other greenhouse gases, significantly contributing to atmospheric pollution and climate instability [12].

The dominant fire regime in peatlands is smoldering combustion, which is a slow, low-temperature and flameless burning process that can persist underground for extended periods ranging from days to months [13–15]. Smoldering peat fires are notoriously challenging to detect and suppress due to their subsurface nature and minimal visible indicators such as flames or smoke (Fig. 1) [16–20]. These fires can inflict severe ecological damage, including vegetation loss, soil degradation, water contamination, and habitat destruction [21–23]. A notable example is

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* Corresponding author.

** Corresponding author. Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong.

E-mail addresses: shaorun.lin@polyu.edu.hk (S. Lin), xy.huang@polyu.edu.hk (X. Huang).

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the catastrophic 1997 Indonesian peat fire, which affected over 11 million hectares of peatland and caused widespread biodiversity loss and ecosystem disruption [24]. Beyond localized impacts, peat fires are major contributors to regional air pollution and global climate change [25,26]. During the 2015 Indonesian wildfires, over one million hectares of peatland burned, with PM_{10} concentrations peaking at 3.76 mg/m^3, triggering one of the most severe haze episodes associated with El Niño events since 1997 [27,28].

Because of their deep-seated and persistent nature, smoldering peat fires present considerable challenges for detection and suppression [9, 29,30]. Several natural suppression mechanisms have been explored in the literature, with rainfall and snowfall identified as cost-effective and environmentally benign solutions [16,31]. These mechanisms primarily function by removing heat (one of the critical elements of the fire triangle), thus disrupting the combustion process [32]. For instance, rainfall intensities of at least 4 mm/h or cumulative rainfall depth exceeding 13 mm have been shown to suppress shallow smoldering fronts, with short-duration intense rain events being more effective than prolonged light rain [16]. Similarly, snow cover exceeding 9 cm can effectively suppress smoldering peat under cold ambient conditions [31]. High peat moisture content and low ambient temperature have also been found to inhibit sustained smoldering [33].

Beyond these natural processes, a range of human-based engineered suppression strategies has also been proposed [17–19,34,35]. Among them, fuel removal through firebreak excavation is widely used to isolate burning areas and contain fire spread [36,37]. In practical firefighting, water remains the most commonly applied extinguishing agent [17,38], though its effectiveness is limited in deeply seated smoldering zones where surface spraying fails to penetrate adequately. Recent laboratory findings suggest that subsurface water injection markedly improves extinguishment efficiency and water conservation, although this technique faces logistical challenges in field deployment [18]. Alternative approaches include the use of firefighting foams [19] and chemical agents designed to induce artificial precipitation [39], though their environmental compatibility, cost, and scalability remain contentious. Therefore, the development of sustainable, efficient, and field-deployable fire suppression technologies for peatlands remains an unresolved challenge.

Notably, coal, which shares similar porous and carbon-rich properties with peat, has been addressed through a wider array of suppression strategies, offering potentially transferable insights [40,41]. Dry ice (solid CO_2), a non-toxic and easily stored agent, has been used to suffocate coal fires by displacing oxygen [41]. However, its slow sublimation under ambient conditions limits its effectiveness in outdoor or field-scale applications. Liquid nitrogen, by contrast, which offers rapid and deep cooling, is chemically inert, and poses no environmental pollution [42]. Its superior cooling capacity has been demonstrated in various fire scenarios, often outperforming water-based suppression systems [43,44]. Despite increasing recognition of the environmental and climatic impacts of smoldering peat fires, research on suppression methods has largely focused on conventional agents such as water, with limited investigation into alternative materials that may offer superior cooling or oxygen displacement. In other words, the application of dry ice and liquid nitrogen to smoldering peat fires has not yet been systematically investigated, representing a critical knowledge gap in current research.

To address this gap, the present study systematically evaluated the performance of four different cooling agents (water, ice, dry ice, and liquid nitrogen) on suppressing underground peat fire and their smoldering spread. We explored their firebreak effect on horizontal smoldering spread on peat samples with initial moisture contents ranging from 10% (dry) to 100% (wet). The extinguishment probability, required agent quantity, and effective cooling duration were measured for both immediate (partial) and sustained (full) suppression. By identifying the relationships between fuel moisture, agent type, and suppression efficiency, this work provides new experimental evidence and practical guidance for selecting optimal suppression strategies in peatland fire management, particularly under diverse environmental conditions.

2. Material and methods

2.1. Peat sample

The peat used in the experiments was sourced from Estonia (Fig. 2), and was characterized by an organic matter content of 96% and a dry bulk density of 145 ± 10 kg/m^3. Prior to experimentation, the peat samples were oven-dried at 90 °C for 48 h to remove residual moisture. Once removed from the oven, the dried peat rapidly absorbed ambient moisture (even in sealed conditions), stabilizing at a moisture content of approximately 10% [45]. This condition, defined as air-dried peat, was maintained by storing the samples in airtight containers to minimize further environmental exposure. To prepare peat samples with varying moisture gradients (up to 100%), the air-dried peat was mixed with pre-measured quantities of water and stored in sealed containers for one week. The mixtures were shaken daily to ensure uniform moisture distribution [46,47]. This preparation protocol has been widely adopted in peat fire literature and has demonstrated consistency and reliability over the past decade [30,48].

2.2. Fire suppression agents

Dry ice and liquid nitrogen, two non-conventional peat fire-extinguishing agents, were selected for investigation in this study due

Fig. 1. (a) Smoldering underground fire and haze phenomena at peatland of Saba, Malaysia in 2023 (courtesy of D. Musa), and (b) Peat smoldering fire suppression campaign (courtesy of ERC).

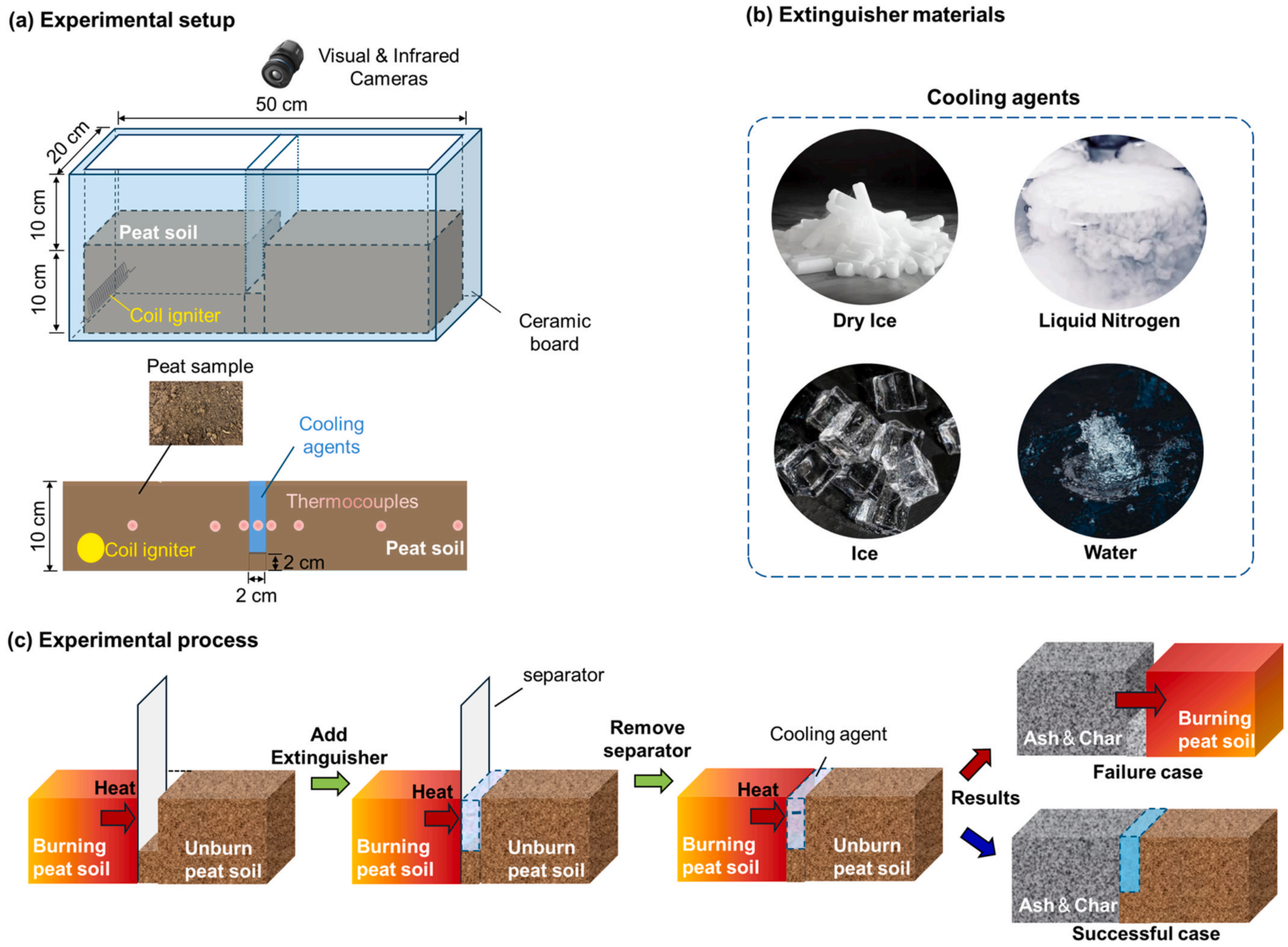

Fig. 2. (a) Schematic diagrams of experimental set-ups, (b) photo of four cooling agents and (c) schematic diagram of experimental process.

to their distinctive thermal and physical properties (summarized in Table 1). Dry ice is the solid form of carbon dioxide (CO_2), which sublimates directly to gas at −78.5 °C [49,50]. With a solid density of 1560 kg/m^3 and a high latent heat of sublimation of 576.5 kJ/kg, dry ice can absorb substantial thermal energy during phase transition [51,52]. Furthermore, it volumetric expansion ratio of about 1:851 from solid to gas [53] allows it to effectively displace oxygen, creating a localized and near anoxic environment that may smother combustion. However, the rapid gas expansion may result in pressure buildup in enclosed environments, posing explosion and asphyxiation risk in poorly ventilated conditions.

Table 1
Physical properties of water, ice, dry ice and liquid nitrogen [49–55].

Property	Water/Ice (H_2O)	Dry Ice (CO_2)	Liquid Nitrogen (N_2)
Gasification point (°C)	100 (boiling)	−78.5 (sublimation)	−196 (boiling)
Density (kg/m^3)	1000/917	1560	808
Latent heat (kJ/kg)	2260 (vaporization)/334 (liquidation)	576 (sublimation)	199 (vaporization)
Specific heat (kJ/kg·K)	~4 (liquid)/~2 (solid)	~0.85 (solid)	~2.04 (liquid)
Vapor density (kg/m^3)	~0.59	~1.98	~1.25
Heat conductivity (W/m·K)	~0.61/2.2	~0.2 (solid)	~0.14 (liquid)
Hazards	N/A	Physical explosion, asphyxiation, frostbite	Frostbite, asphyxiation

Liquid nitrogen is a cryogenic fluid that boils at −196 °C, with a liquid density of 808 kg/m^3 [54]. It possesses a latent heat of vaporization of about 199 kJ/kg and a specific heat capacity of 2.04 kJ/kg·K [55], giving it powerful cooling capabilities upon contact with hot materials. With a gas expansion ratio of 1:694, nitrogen vapor can also displace oxygen and create suffocation hazards in confined areas. Meanwhile, direct contact with skin or tissue can result in severe cold burns or frostbite. Despite these limitations, its rapid, residue-free cooling and chemical inertness make (liquid) nitrogen a widely used for fire suppression.

In addition to dry ice and liquid nitrogen, two conventional agents, ice and water, were also included for comparison. Water represents the most widely used and accessible suppressant in practical peat fire management, while ice was selected as its solid-phase counterpart with a slower release of cooling energy. Although they do not share the same cryogenic properties as dry ice and liquid nitrogen, incorporating ice and water into the study allows for a direct performance comparison under identical experimental conditions. This ensures that the suppression effectiveness of cryogenic agents can be fairly evaluated against conventional strategies, thereby providing a systematic assessment of potential firefighting strategies for smoldering peat fires.

2.3. Experimental setup

The experimental setup is illustrated in Fig. 2 and primarily consists of a custom-built reaction container and an electrical ignition system. The reaction container was an open-top rectangular box constructed from 1 cm thick ceramic fiber board, chosen for its thermal insulation and fire resistance. The internal dimensions of the reactor were 50 cm (l) × 20 cm (w) × 20 cm (h). To further minimize heat loss and prevent gas leakage during smoldering, the external surfaces were wrapped with aluminum foil tape.

Ignition was achieved using a resistive metal coil rated at 100 W, positioned at one end of the container (see Fig. 2). This power setting has been validated in previous studies as sufficient to initiate self-sustaining smoldering combustion in peat [31,48]. The designated fire-extinguishing zone was located at the geometric center of the reaction container, with a uniform width of 2 cm (Fig. 2). In practice, peat is rarely removed entirely during firefighting operations because its thickness is not uniform; therefore, a residual layer of roughly 2 cm was retained in the fire-extinguishing zone to replicate field conditions.

Thermocouples were used to record the temperature evolution during the reaction, which were positioned 5 cm above the bottom of the container. Each thermocouple probe was horizontally inserted 10 cm into the peat layer, positioning the sensing element near the centerline of the container (Fig. 2). Thermocouples were spaced at 10 cm intervals along the longitudinal axis of the container, with three probes located within and adjacent to the extinguishing zone to capture spatial variations in temperature during suppression. Visual and thermal imaging systems were installed above to monitor the fire phenomena and record surface temperature dynamics.

2.4. Test procedures

At the beginning of the experiment, except for the extinguishing zone, the peat samples were evenly distributed within the reaction container, with a thickness of 10 cm. The heating duration required to initiate self-sustaining smoldering propagation varied between 20 min (dry peat) to 40 min (100% MC peat). After ignition, the smoldering front was allowed to propagate longitudinally across the container (see Fig. 2(c)). Note that the underground burning front was not the same as that the top surface, because of its overhang structure [46], so the

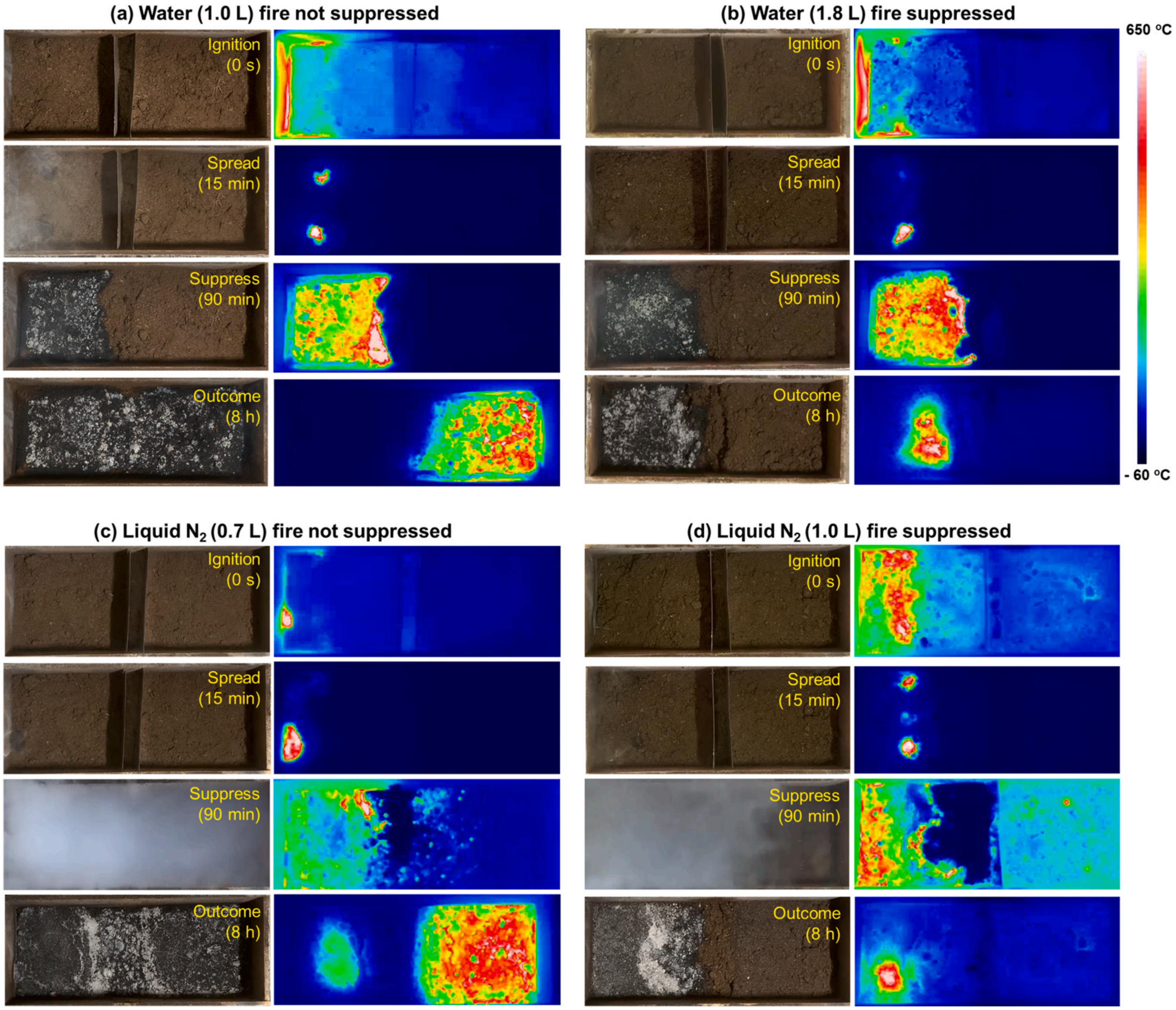

Fig. 3. Suppressing smoldering dry peat ($MC_p \approx 10\%$) via liquid agents, (a) failed suppression by 1 L water, (b) successful suppression by 1.8 L water, (c) failed suppression by 0.7 L liquid nitrogen, and (d) successful suppression by 1 L liquid nitrogen. More details are seen in Videos S1 and S2.

imbedded thermocouples could help monitor the in-depth fire front. After the smoldering front advanced 20 cm, the selected extinguishing agent was applied to the extinguishing zone within 3 s, after which the metal separators were removed to allow direct interaction between the smoldering front and the suppressant. All experiments were conducted under controlled laboratory conditions, with ambient temperature maintained at about 25 °C, relative humidity at around 50%, and atmospheric pressure at 1 atm. To enhance repeatability and reliability, a minimum of ten replicate tests were conducted for each experimental condition, including different MCs and extinguishing agents.

3. Experimental phenomena

3.1. *Suppression using water*

Water was first selected for comparison because of its widespread usage and accessibility. Once the water is sprayed, water quickly reduced surface temperatures to near ambient levels, as illustrated in Fig. 3(a–b) and Video S1. However, the cooling effect of water was transient that required repeated or continuous spray to maintain. Because of its fluid nature, water quickly flows downward without sufficiently cooling the burning zone, unlike other solid suppression agents.

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Nevertheless, water still offers practical advantages: it is abundant, inexpensive, and locally available, making it suitable for field-scale deployment. However, streams of water always flow along paths of least resistance driven by gravity. In the porous and uneven terrains such as peatlands, water spray often results in uneven distribution and incomplete suppression [56].

3.2. *Suppression using liquid nitrogen*

The liquid nitrogen exhibited a markedly different suppression mechanism due to its extremely low temperature and volatility, as illustrated in Fig. 3(c–d) and Video S2. Once the extremely cold liquid nitrogen gets in contact with smoldering fire front and the soil layer, it rapidly vaporizes, showing vigorous boiling, bursting white ash, black char and peat particles and creating dense vapor plumes. The bursting solid particles may not be fully cooled by liquid nitrogen. These hot particles may re-coat the fuel surface and act like embers, which can lead to the re-ignition and spread of smoldering fire. Furthermore, this behavior poses a real-world hazard, as airborne hot particulates may harm firefighters or introduces new fire risks.

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From the thermocouple data in Fig. 4(c–d), the in-depth peat temperature initially dropped to around −170 °C, suggesting the immediate suppression capability of liquid nitrogen [42]. Because liquid nitrogen is

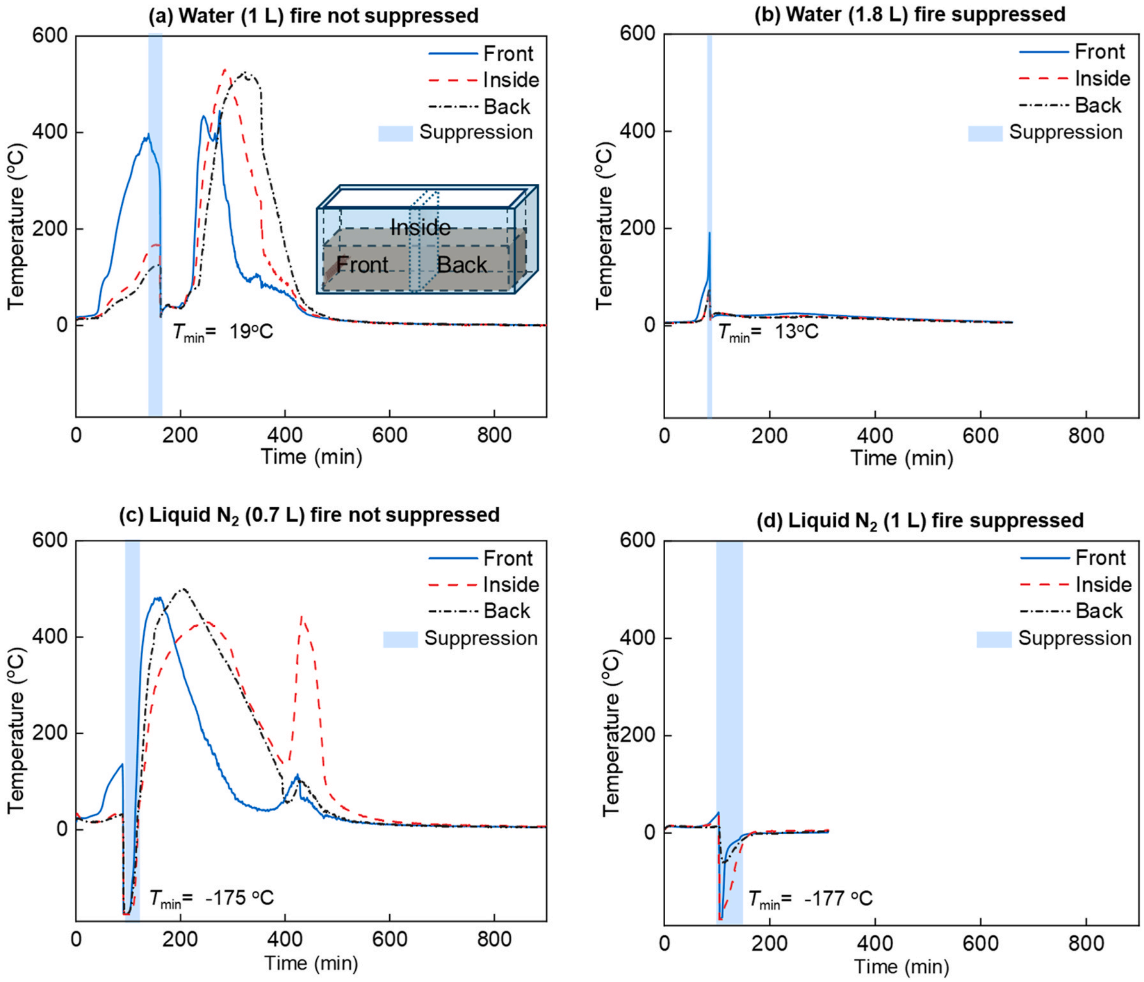

Fig. 4. Temperature evolutions of smoldering dry peat ($MC_p \approx 10\%$) suppressed with liquid agents: (a) failed suppression by 1 L water, (b) successful suppression by 1.8 L water, (c) failed suppression by 0.7 L liquid nitrogen, and (d) successful suppression by 1 L liquid nitrogen, where the blue shadow the blue shaded regions represent the time interval during which the applied cooling agent is actively effective, that is, before it is completely consumed, evaporated, or sublimated. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

vaporized rapidly, it creates a large volume of nitrogen gas that displaced oxygen while simultaneously cooling the substrate. However, such smothering mechanism is very minor, because smoldering combustion is more resistant than flaming that can exist under very low oxygen concentration. The extremely fast evaporation of liquid nitrogen and short-lived cooling do not provide a sustained fire suppression. With 0.7 L liquid nitrogen, the smoldering front was able to reignite as hot spots still exist in surrounding peat soil. Additionally, the bursting hot particles land on the unburnt surface, aiding the repropagation of peat fire.

In a successful fire suppression with 1 L liquid nitrogen, a portion of its cooling quickly freezes the soil water within the peat, rather than directly cooling the burning soil, so the frozen soil could enhance the thermal absorption and prolonging fire suppression effect, similar to the permafrost [33]. Although the suppression performance of liquid nitrogen is clearly better than water, its fluid nature makes its cooling effectiveness low, transient, and not sustained.

3.3. *Suppression using ice*

When the ice (0 °C) was applied to the extinguishing zone, there was only minimal level of white smoke (condensed water vapor), as seen in Fig. 5(a–b) and Video S3. Infrared imaging shows that the internal temperature dropped to around 0 °C (also see thermocouple data in Fig. 6(b)), indicating a better direct cooling than water while a lower direct cooling than water liquid nitrogen. In a typical no-suppression case with 0.8 kg ice in Fig. 5(a), we can see that ice melts rapidly and fails to maintain cooling long enough to inhibit peat fire spread.

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By increasing mass of ice to 0.9 kg in Fig. 5(b, a) successful fire suppression can be achieved, when the melted ice is sufficient to saturate the local substrate and prolong cooling effect. Although the suppression effect of ice is better than water, its latent heat of melting is low (1/7 of evaporation heat), so it rapidly melts into water and flows away. Moreover, because of a lower density and inflexibility in shape, ice required more storage volume and freezing facilities than water, presenting logistical drawbacks in transport, further limiting its wide

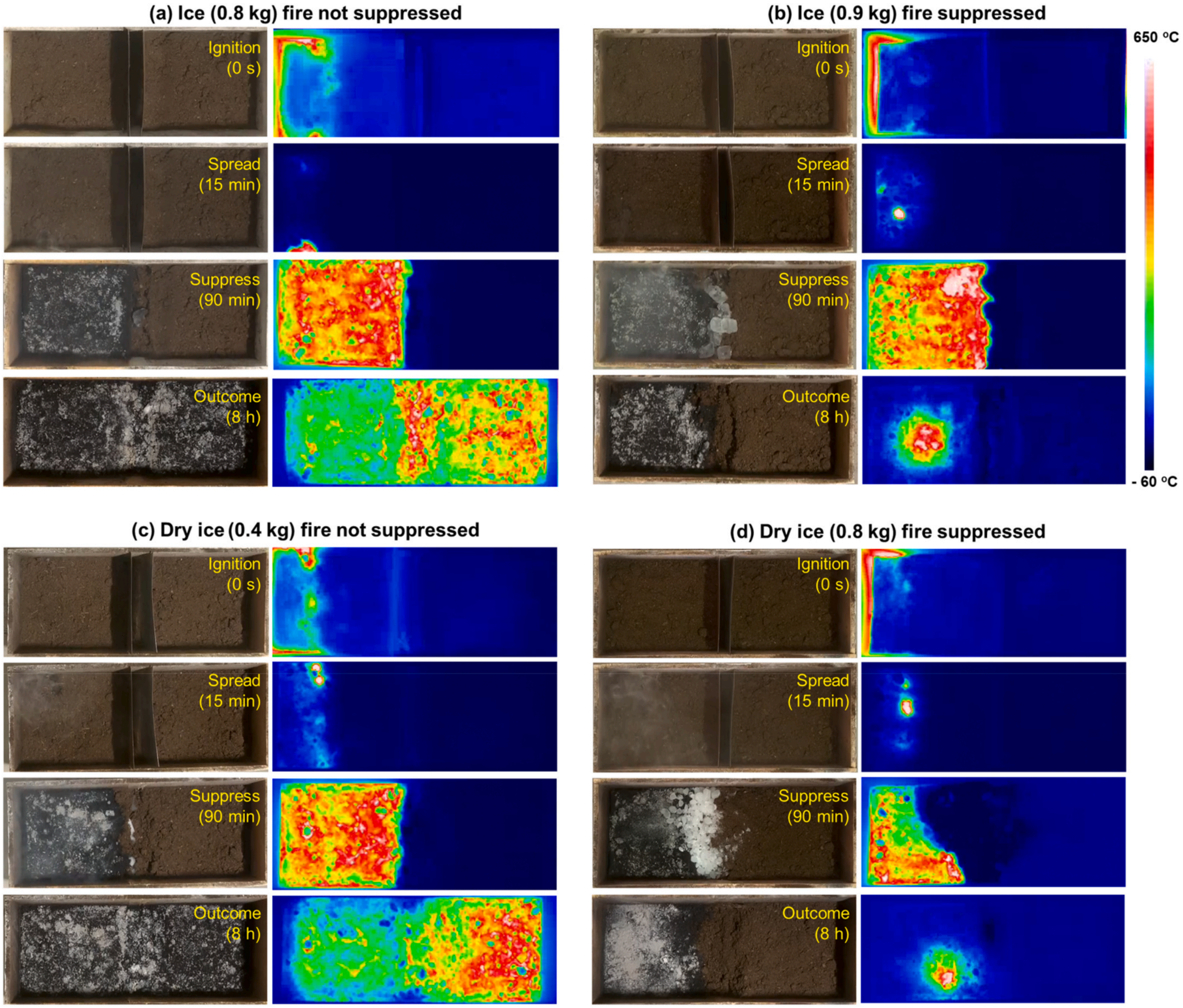

Fig. 5. Suppressing smoldering dry peat ($MC_p \approx 10\%$) via solid agents, (a) failed suppression by 0.8 kg ice, (b) successful suppression by 0.9 kg ice, (c) failed suppression by 0.4 kg dry ice, and (d) successful suppression by 0.8 kg dry ice. More details are seen in Videos S3 and S4.

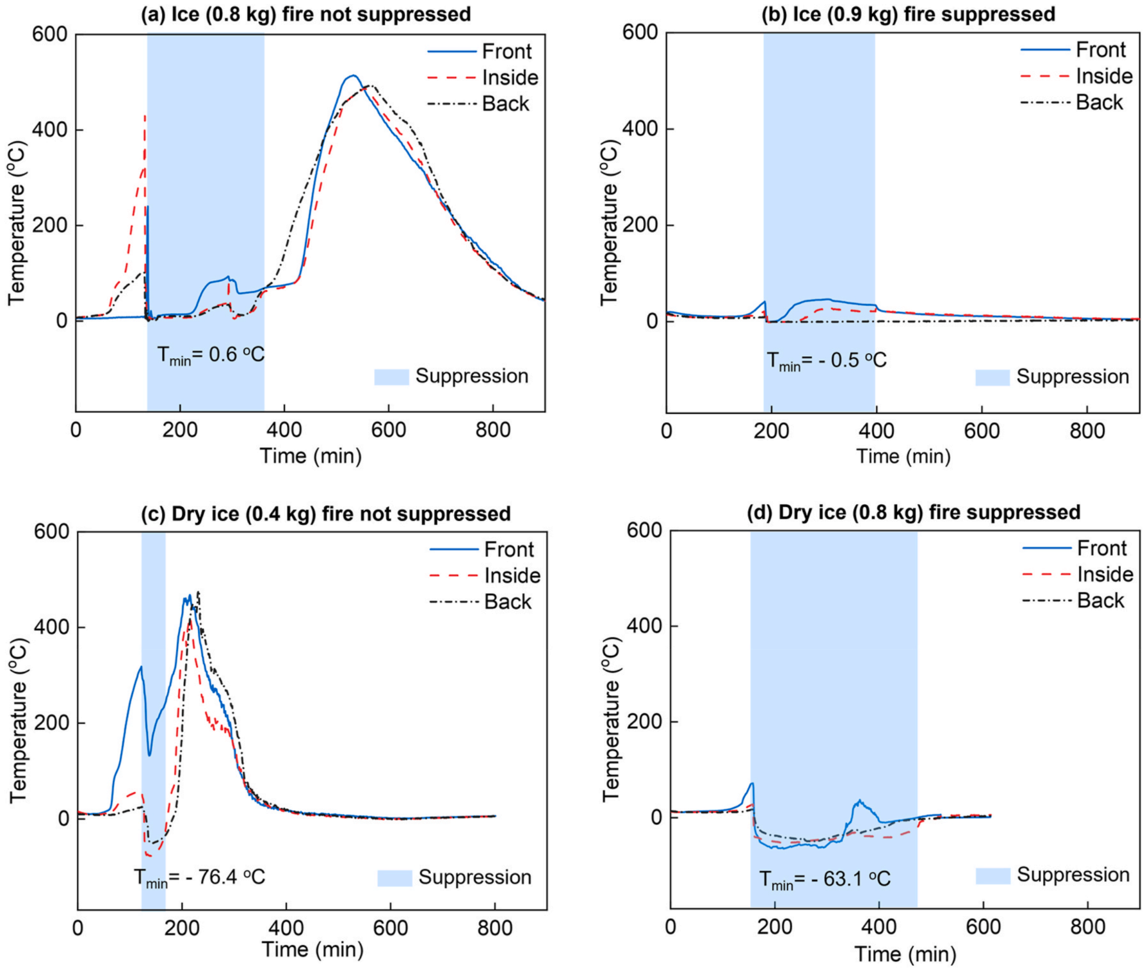

Fig. 6. Temperature evolutions of smoldering dry peat ($MC_p \approx 10\%$) suppressed via solid agents, (a) failed suppression by 0.8 kg ice, (b) successful suppression by 0.9 kg ice, (c) failed suppression by 0.4 kg dry ice, and (d) successful suppression by 0.8 kg dry ice.

practice in firefighting.

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3.4. *Suppression using dry ice*

The extinguishing behavior of dry ice shares similarities with ice, as both initially existed in the solid state and released energy as they undergo the phase-change process. Fig. 5(c–d) and Video S4 presents the typical suppression process by using dry ice. Once the smoldering front extended to 20 cm, dry ice was introduced into the designated extinguishing zone immediately, where visible white smoke emerged. The observed white smoke is likely the condensed water vapor.

Once in touch with the dry ice, the in-depth soil temperature in the contact zone rapidly dropped to −70 °C (Fig. 6(c)). In a no-suppression case, the small amount of dry ice (0.4 kg) was insufficient to maintain subzero temperatures for an effective duration, leading to eventual reignition. In contrast, successful suppression was consistently observed when the quantity of dry ice surpassed a threshold (e.g., 0.8 kg in Fig. 5 (d)), allowing not only for significant cooling but also for prolonged oxygen displacement. Regardless of extinguishment success, the smoldering rate was significantly reduced by dry ice, attributed to dry ice's slow sublimation, which allows for a gradual energy release over time, a favorable characteristic for sustained suppression of smoldering fire.

However, safety concerns arise with dry ice usage. In confined environments, dry ice can generate static electricity when in contact with metal surfaces [57]. If pyrolysis gases have accumulated, this could potentially trigger explosions or secondary ignition, posing serious hazards for enclosed or underground smoldering fire sites.

4. Results and discussion

4.1. *Extinguishment probability and suppression limits*

Fig. 7 summarizes the suppression performance of (a) liquid and (b) solid fire suppression agents for different peat MCs. Note that each data point represents at least ten experimental replicates, with extinguishment probability calculated as the proportion of trials in which the smoldering front was halted before reaching the far end of the reactor. In this study, 50% was set as the threshold between high and low suppression probabilities; however, the 50% threshold is not intended to represent a physical limit between suppression and non-suppression, but rather a conventional statistical reference used to distinguish conditions under which extinguishment is more likely than failure. This criterion allows the minimum effective agent quantity to be identified in a consistent and comparable manner across different suppressants.

For the liquid suppressants in Fig. 7(a), they display a similar moisture dependence, but with steeper performance gains as MC_p increased. For liquid N_2, complete suppression (100%) of fire in dry peat ($MC_p = 10\%$) requires about 1.1 L (or 0.9 kg), while for wet peat of $MC_p = 100\%$, only about 0.4 mL ($\approx$0.32 kg) is needed. The improvement with higher MC_p can be attributed to the synergistic effect of rapid cooling and latent heat storage: as liquid nitrogen contacts moist peat, part of the water in the fuel freezes, forming a temporary thermal buffer

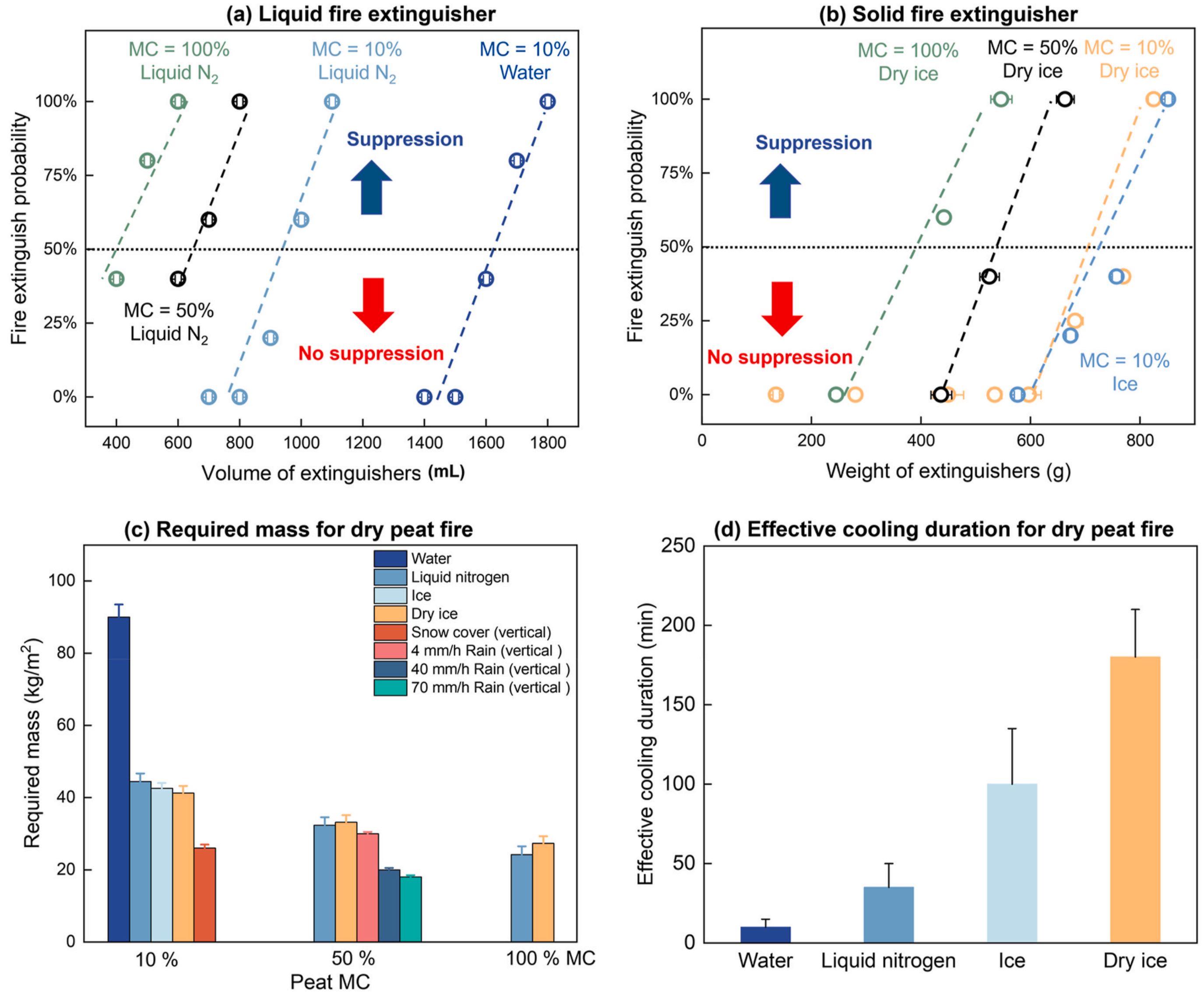

Fig. 7. (a) Suppression performance of water and liquid nitrogen, (b) suppression performance of dry ice and ice, (c) required mass using different cooling agents, where rain and snow cover were included for comparison [16,31], and (d) effective cooling duration for four agents ($MC_p = 10\%$).

that slows heat recovery and delays re-ignition. Water, by contrast, was consistently less efficient. For dry peat (10% MC, liquid nitrogen must be doubled for complete suppression, and in many borderline cases the smoldering front resumed once local temperatures rose above the pyrolysis threshold.

For the solid suppressants in Fig. 7(b), dry ice exhibited a distinct threshold behavior. At low moisture content ($MC_p = 10\%$), the minimum mass for complete (100%) extinguishment was about 0.8 kg, whereas at high moisture content ($MC_p = 100\%$) this value dropped to about 0.5 kg. Below these thresholds, suppression often failed because the sublimation-driven cooling did not penetrate deeply enough into the smoldering zone. In unsuccessful trials, localized cooling near the application point still slowed propagation but did not halt it entirely; the combustion front eventually bypassed the cooled region, reigniting downstream fuel. Ice showed a similar pattern, but its required threshold mass was slightly higher than that of dry ice at low MC_p, likely because melting water drained away before fully absorbing the heat needed to quench smoldering.

A direct comparison on a mass basis is presented in Fig. 7(c), with all liquid volumes converted using their respective densities. At $MC_p = 10\%$, the required mass per square meter for dry ice (≈41 kg/m^2), ice (≈42 kg/m^2), and liquid nitrogen (≈44 kg/m^2) were surprisingly similar, suggesting that when normalized for mass, these agents deliver comparable net cooling capacities under dry conditions. Water, however, required more than around 90 kg/m^2, highlighting its lower cooling effectiveness under current experimental conditions. This difference arises not only from water's lower latent heat of vaporization compared to the sublimation or evaporation of cryogenic solids and liquids, but also from its rapid drainage in porous peat, which limits residence time and sustained cooling.

This study also compared results with prior experiments involving natural rainfall and snow (converted to equivalent precipitation) [16, 31]. For example, the findings demonstrate that stronger rainfall intensity requires less total water volume for extinguishment. This occurs because under low-intensity rainfall, water evaporates due to high temperatures before penetrating to the smoldering front. Furthermore, as compared in Fig. 7(c), earlier studies required significantly less water to suppress peat fires because they focused solely on vertical smoldering propagation, allowing applied water to concentrate entirely on the burning zone [16,31]. In contrast, our experiment emphasizes horizontal smoldering spread, the primary mode of wildfire expansion in natural settings, which aligns with empirical observations and practical firefighting challenges.

The duration of effective cooling, as used in this study, is defined as the time interval from the application of the suppressant to its complete consumption within the fuel bed. Fig. 7(d) shows that this duration varied significantly across suppressants. Solid agents, particularly dry ice, maintained subcritical temperatures over extended periods after application, owing to their slow sublimation rates and sustained release of cold CO_2 gas. This prolonged cooling effect contributed not only to complete extinguishment in successful trials but also to markedly slower smoldering progression in unsuccessful cases, effectively buying time for further firefighting measures. Ice offered intermediate cooling durations, limited by melting and runoff, while liquid nitrogen's cooling was immediate yet transient, with temperatures rapidly rebounding as vapor dispersed. Water's cooling duration was variable and generally insufficient for sustained suppression, especially at low MC_p.

Table 2 shows the performance of different fire extinguishing agents observed and summarized in the experiment. Water and ice are easy to operate and obtain, with no need to worry about threats to the environment or personal safety posed by the fire extinguishing agents themselves. However, the use of dry ice requires professional training, as it is highly likely to cause frostbite. Moreover, the sustained or instantaneous extreme low temperature will have a huge impact on the soil environment, killing soil microorganisms and soil animals and causing irreversible damage.

The influence of moisture content was consistent across all agents: higher MC_p reduced the quantity required for complete suppression. This can be explained by the lower total heat release of wetter fuels and by the additional cooling from freezing and thawing of inherent moisture. However, the magnitude of this effect varied, that is, liquid nitrogen benefited most from increased MC_p, whereas dry ice showed a more moderate improvement. These trends align with previous studies on smoldering suppression, which emphasize that both energy balance and oxygen availability govern extinguishment outcomes [41,53,58,59].

The observed unsuccessful cases provide further insight into mechanism-specific limitations. For dry ice and liquid nitrogen, insufficient application often led to a cooled but still-oxidizing layer, where smoldering could bypass the treated region. For ice and water, the main failure mode was incomplete penetration or rapid drainage, leaving deeper layers unaffected. Notably, even in unsuccessful attempts, solid suppressants, particularly dry ice, demonstrated a superior ability to slow fire progression compared to liquids. This advantage stems from their capacity to cool the fuel bed for a longer period, thereby reducing the rate of smoldering front advancement. In firefighting practices, a complete suppression may not be immediately achievable. Then, such a prolonged cooling effect could still provide critical time for containment efforts or secondary suppression interventions.

Table 2

Performance of water, ice, dry ice and liquid nitrogen on suppression underground peat fire.

Parameter	Water (H_2O)	Ice (H_2O)	Dry Ice (CO_2)	Liquid Nitrogen (N_2)
Original phase	Liquid	Solid	Solid	Liquid
Suppression effectiveness	Low	High	Very high	Medium
Firefighting operation	Easy	Easy	Easy	Difficult
Cost of agent	Low	Low	Low	High
Cooling mechanism	Convection	Melting	Sublimation	Convection + evaporation
Smothering effect	None	None	Yes, but minor	Yes, but minor
Environmental impact	None	None	Green house	Damage soil ecosystem
Personnel danger	None	None	Frostbite	Frostbite

4.2. Heat transfer analysis for suppression limits

To understand the minimum requirement of extinguishing agents for halting the smoldering spread of peat fire, the energy conservation is explored, as shown in Fig. 8. Smoldering spread can be regarded as a continuous ignition of virgin fuel initiated by adjacent burning fuel [47,60]. When a cooling agent is applied, fire propagation will cease if the energy released from combustion is insufficient to both (i) compensate for the heat loss due to the cooling agent and (ii) raise the temperature of virgin peat to the minimum smoldering ignition threshold.

Based on this principle, the following energy balance was formulated:

$$Q_p = Q_s + Q_c \tag{1}$$

Which can be further re-organized as

$$m''_p \Delta H_s A \Delta t = \rho_p c_p A \delta (T_s - T_a) + Q_c \tag{2}$$

The left-hand side describes the total energy released by the combustion of peat over the effective cooling duration (Q_p), where $m''_p = 1$ g/m^2·s is the burning mass flux of peat, $\Delta H_s = 20$ MJ/kg is the specific heat of smoldering combustion [16], $A = 0.002$ m^2 is the smoldering burning area, and Δt is the effective cooling duration measured from test (e.g., Fig. 7(d)). The right-hand side consists of two terms: the sensible heat absorbed by the peat matrix ($Q_s = \rho_p c_p A \delta (T_s - T_a)$) and the heat absorbed by the cooling agent (Q_c), where ρ_p is the bulk density (kg/m^3), $c_p = 1.4$ kJ/kg-K is the specific heat capacity, $\delta = 0.05$ m is the smoldering front thickness, $T_s = 275$ $^{\circ}$C is the minimum smoldering ignition temperature [47], and $T_a = 25$ $^{\circ}$C is the ambient temperature.

For dry ice, heat removal occurs through sublimation, with a latent heat of $L_{sub} = 576$ kJ/kg. Therefore, Eq. (2) could be written as:

$$m''_p \Delta H_s A \Delta t = m_{di} L_{sub} \text{ (dry ice)} \tag{3}$$

From the experimental observation, complete suppression of air-dried peat required a duration of 175 min (Fig. 7(d)). Substituting into Eq. (3), the required dry ice mass is

$$m_{di} = \frac{m''_p \Delta H_s A \Delta t - \rho_p c_p A \delta (T_s - T_a)}{L_{sub}} \approx 0.72 \text{ kg} \tag{4}$$

In practice, however, a fraction of the dry ice sublimated into the surrounding air before participating in heat removal. This explains why the experimental suppression demand exceeded the theoretical prediction and supports the observed results.

For liquid nitrogen, suppression occurs via vaporization, with a latent heat of $L_{vap} = 199$ kJ/kg. Therefore, Eq. (2) can be expressed as:

$$m''_p \Delta H_s A \Delta t = \rho_p c_p A \delta (T_s - T_a) + m_{ln} L_{vap} \text{ (liquid nitrogen)} \tag{5}$$

Using the density of liquid nitrogen ($\rho_{ln} = 808$ kg/m^3), the required volume (V_{ln}) to fully halt the spread of smoldering peat fires can be calculated as

$$V_{ln} = \frac{m_{ln}}{\rho_{ln}} = \frac{m''_p \Delta H_s A \Delta t - \rho_p c_p A \delta (T_s - T_a)}{L_{vap} \rho_{ln}} \approx 0.57 \text{ L} \tag{6}$$

This calculation highlights the compactness of liquid nitrogen as a suppression agent, since relatively small volumes can absorb large amounts of heat. However, experiments revealed that liquid nitrogen undergoes substantial vaporization before effective interaction with the peat layer. Rapid boiling on contact with hot porous fuel surfaces reduces the cooling efficiency and leads to consumption far above the theoretical minimum.

Comparison between theoretical predictions and measured usage provides important insight. Only about 90% of the dry ice and 50% of the liquid nitrogen applied during experiments contributed directly to suppression, with the remainder lost through premature sublimation or

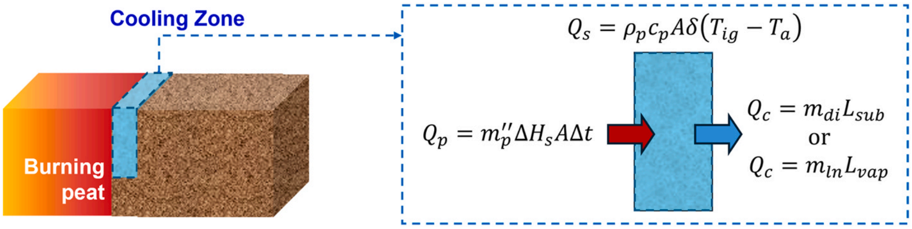

Fig. 8. Schematic diagram of heat transfer analysis, where fire extinction is considered as a failed ignition of fresh peat cooled by suppression agent.

vaporization. These inefficiencies emphasize the critical role of delivery methods: effective suppression depends not only on the thermodynamic properties of the agents but also on their contact time, distribution within the porous medium, and resistance to environmental heat exchange.

4.3. Limitations and perspectives

This study provides a controlled and systematic comparison of four extinguishing agents (i.e., water, liquid nitrogen, ice, and dry ice) for suppressing smoldering peat fires, yielding quantitative insights into extinguishment probability, required quantities, and effective cooling durations. However, several limitations must be acknowledged before applying to firefighting practices.

Firstly, the experiments were conducted in a standardized laboratory reaction vessel with fixed geometry, peat bulk density, and particle size distribution. In natural peatlands, the substrate exhibits substantial heterogeneity in porosity, layering, mineral inclusions, and organic matter content, all of which influence heat transfer, smoldering propagation, and suppressant infiltration. Consequently, the absolute suppressant quantities identified here may not directly translate to real-world conditions, where environmental heat losses, wind-driven oxygen supply, and irregular combustion fronts can significantly alter suppression dynamics.

Secondly, the tested peat has a uniform and controlled moisture contents, whereas natural peat profiles display considerable spatial and temporal variation in moisture distribution. Although the results show that higher moisture content enhances suppression efficiency, particularly for liquid nitrogen due to its ability to freeze pore water and release stored cooling energy gradually, localized dry regions in the field could still permit fire persistence or reignition. Thus, the observed moisture–suppression relationships should be applied to field scenarios with caution.

Thirdly, this work emphasizes the cooling effects of suppression while overlooking potential environmental and ecological impacts. Extreme localized cooling from dry ice or liquid nitrogen application could cause physical damage to root systems, soil biota, and hydrological function. Similarly, large-scale application of water or ice in peatlands may lead to surface flooding, peat destabilization, or increased erosion. Future suppression strategies should incorporate ecological impact assessments alongside thermal performance metrics to ensure environmental sustainability.

Both dry and wet firebreaks are widely used to block underground smoldering peat (Fig. 9), including directly digging trenches, constructing canals, and using physical barriers. However, these methods all consume substantial human and material resources. Furthermore, if the scale of construction is insufficient to cover all propagation paths before the smoldering fire reaches the isolation site, the smoldering fire is highly prone to overflow, leading to failed fire suppression or reignition. The proposed "**cooling fire barrier**" uses different cooling agents to quench smoldering fire front in soil. Even if there are propagation paths not covered by the fire-extinguishing agents, the cooling barrier will slow down the propagation speed, thereby providing sufficient time to ensure the success of fire suppression.

Fourthly, the duration of effective cooling in this study was defined as the time between suppressant application and its complete consumption. While this metric provides a consistent basis for comparison, field suppression operations often involve variable application rates, intermittent replenishment, and partial mixing with unburnt fuel layers. Such complexities could alter the duration and magnitude of cooling in ways not captured by the current laboratory protocol.

Looking forward, further work should bridge the gap between laboratory and field conditions through larger-scale experiments in heterogeneous peat profiles, under realistic weather and oxygen supply conditions. The integration of advanced measurement techniques such as subsurface temperature mapping, gas concentration monitoring, and in situ heat flux sensors would improve understanding of the coupled heat and mass transfer processes driving suppression outcomes. Moreover, hybrid suppression approaches may warrant exploration; for example, an initial application of a fast-acting liquid suppressant (e.g., liquid nitrogen) could provide immediate cooling and oxygen displacement, followed by a slow-sublimating solid suppressant (e.g., dry ice) to maintain prolonged cooling and delay reignition.

In summary, while dry ice demonstrated superior sustained suppression capability under the controlled conditions of this study, practical deployment in peatland environments must account for operational feasibility, logistics, cost, and environmental safety. These considerations form a crucial bridge between the mechanistic insights presented here and the development of integrated, field-ready strategies for the effective and sustainable management of smoldering peat fires.

5. Conclusions

This study systematically evaluated the suppression performance of four agents (i.e., dry ice, ice, liquid nitrogen, and water) on smoldering peat fires under controlled laboratory conditions. By quantifying

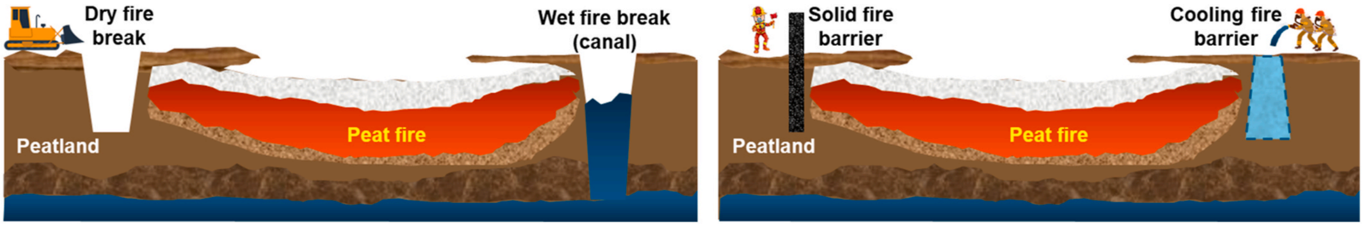

Fig. 9. Different fire breaks and barriers for controlling underground smoldering peat fires.

extinguishment probability, required agent quantity, and duration of effective cooling across a range of peat moisture contents, the work provides a mechanistic basis for selecting and optimizing suppression strategies.

The results demonstrate that agent type and peat moisture jointly determine suppression outcomes. Dry ice exhibited the most consistent and sustained suppression performance, requiring smaller quantities than other agents at low moisture contents and maintaining long effective cooling durations due to its slow sublimation and combined cooling–oxygen displacement effect. Liquid nitrogen showed strong instantaneous cooling, particularly at high moisture contents where frozen pore water prolonged the cooling effect, but its rapid evaporation often led to temperature rebound and reignition. Ice performed moderately well but was limited by its rapid melting and larger storage volume. Water, despite being the most accessible and widely used agent, required twice the mass of dry ice to achieve equivalent suppression, and its effectiveness was hampered by rapid drainage and incomplete coverage of the smoldering zone.

Comparison shows that even if the fire is not fully extinguished, solid agents, especially dry ice, are more effective at slowing smoldering propagation than liquid agents, owing to their longer residence time and sustained heat extraction. These findings suggest that for smoldering peat fires, particularly under low-moisture conditions, slow-releasing solid suppressants are more effective. However, field implementation must consider additional factors such as logistical feasibility, environmental impact, and operational safety.

Ultimately, while no single agent can universally address the challenges of smoldering peat fire suppression, the quantitative framework developed in this study provides a foundation for selecting and combining agents to achieve both immediate and sustained suppression in diverse peatland fire scenarios. Future work should expand on these controlled experiments through field-scale validation under realistic environmental conditions, heterogeneous peat profiles, and variable weather influences. Such studies will help translate the mechanistic insights gained here into practical, ecologically responsible suppression strategies.

CRediT authorship contribution statement

Yichao Zhang: Writing – original draft, Methodology, Investigation, Formal analysis. **Yuying Chen:** Investigation, Data curation. **Yunzhu Qin:** Resources, Investigation, Data curation. **Yizhou Li:** Resources, Data curation. **Yuxin Zhou:** Resources, Data curation. **Zifan Zhang:** Resources, Investigation, Data curation. **Yuting Jiang:** Resources, Data curation. **Shaorun Lin:** Writing – review & editing, Methodology, Formal analysis. **Xinyan Huang:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, 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.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.firesaf.2026.104772.

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