



Design and Experimental Validation of a Low-Cost Adaptive Firebreak for Waterless Peatland Fire Control and Reignition Prevention

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ABSTRACT

Peatland fires pose persistent environmental challenges because subsurface smoldering can continue after visible flames disappear, increasing the difficulty of suppression and the risk of reignition. Conventional water-based firefighting may be constrained by water availability, transportation requirements, and difficulties delivering sufficient cooling to underground combustion zones. This study proposes GAMBUT-LOCK, a low-cost adaptive firebreak concept designed to support waterless peatland fire control using locally sourced mineral materials, mechanically simple barrier construction, and subsurface temperature monitoring. The proposed research adopts a qualitative, design-oriented experimental approach involving material characterization, prototype development, controlled laboratory observations, and comparative evaluation of barrier configurations. The assessment will focus on the interruption of smoldering propagation, residual heating, potential reignition, operational simplicity, material requirements, and environmental compatibility. Unlike approaches that rely primarily on specialized extinguishing agents or complex thermal infrastructure, GAMBUT-LOCK emphasizes targeted intervention, locally available resources, and repeated thermal verification. Its proposed novelty lies in integrating hotspot identification, adaptive mineral barrier placement, and post-intervention monitoring within a practical firebreak framework. As the prototype has not yet been experimentally validated, its effectiveness and cost advantages remain to be established. The study is expected to provide an initial engineering basis for developing affordable, resource-efficient firebreak technology for tropical peatlands, subject to experimental validation and further assessment of environmental performance and patentability.

Keywords: Peatland Fires; Waterless Fire Suppression; Adaptive Firebreak; Mineral Barrier; Smoldering Combustion; Locally Sourced Materials; Reignition Prevention; GAMBUT-LOCK

Field: Environmental Engineering; Fire Safety Engineering; Materials Engineering; Mechanical Engineering; Environmental Technology and Innovation; Low-Cost Fire Suppression Technology; Sustainable Peatland Fire Management

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INTRODUCTION

Peatland fires represent a persistent environmental and technological challenge because combustion can propagate beneath the ground surface through porous organic deposits, allowing smoldering fronts to remain active even after visible flames have disappeared. Unlike flaming combustion, smoldering peat fires can persist under limited oxygen availability, spread irregularly through heterogeneous fuel layers, and reignite when

favorable thermal and oxygen conditions return (Marfella et al., 2025). These characteristics make peatland fire suppression fundamentally different from conventional surface firefighting, where visible flames and accessible fuel sources often define the primary intervention targets. The challenge is particularly significant in tropical peatlands, where prolonged dry periods, drainage, land-use change, and accumulated combustible organic matter can create conditions conducive to persistent underground combustion. Consequently, effective peatland fire management requires technologies that address not only immediate flame suppression but also subsurface fire propagation, residual heat, and the risk of reignition.

Conventional peatland firefighting frequently relies on water-based suppression, including direct application, pumping, and saturation of affected soil layers (Zhang et al., 2026). Although water can provide substantial cooling, its effectiveness may be constrained by limited accessibility, high transportation requirements, uneven infiltration, and the difficulty of delivering sufficient quantities to deep-seated combustion zones. Water demand can become particularly problematic in remote peatland areas where surface water is scarce, contaminated, or difficult to transport during severe fire events. Furthermore, applying water to the surface does not necessarily guarantee that heat has been eliminated throughout the subsurface peat profile. These limitations motivate the development of alternative suppression strategies that reduce dependence on water while maintaining effective control over the movement of underground combustion fronts. However, replacing water with another consumable agent may simply transfer the logistical burden from one material to another. A more fundamental technological shift is therefore needed: from resource-intensive suppression of entire affected areas toward spatially targeted interruption of fire propagation.

One promising direction is the use of physical firebreaks to interrupt the continuity of combustible peat and restrict the movement of smoldering fronts. Nevertheless, conventional firebreaks are not inherently effective against underground peat fires because combustion can propagate beneath, around, or beyond an inadequately designed barrier. Their performance depends on barrier geometry, depth, thermal properties, surrounding peat characteristics, and the spatial distribution of residual heat. Similarly, mineral materials cannot automatically be considered effective fire suppressants merely because they are noncombustible; under certain conditions, they may conduct heat, leave pathways for oxygen transport, or fail to isolate the active combustion zone. The central engineering challenge is therefore not simply to introduce mineral material into peatland, but to determine how a barrier should be positioned, constructed, and verified so that it interrupts subsurface fire propagation without requiring extensive excavation or continuous application of water. Addressing this challenge requires an integrated design approach combining material characterization, adaptive barrier geometry, subsurface temperature monitoring, and systematic evaluation of reignition risk (Susanti et al., 2026).

Recent research has begun to explore alternative approaches to subsurface peat fire control, demonstrating both the potential and limitations of existing technologies. (Jiang et al., 2026) experimentally investigated firebreak configurations for smoldering peat and identified the importance of peat-layer thickness and moisture conditions in determining whether combustion could be interrupted. More recently, (Musa et al., 2026) demonstrated that buried heat pipes could reduce peak smoldering temperatures and, under certain laboratory conditions, suppress combustion propagation by modifying subsurface heat transfer. Meanwhile, experimental comparisons of water, ice, dry ice, and liquid nitrogen have highlighted the potential of non-water-based suppression agents, although their material requirements, cooling duration, and operational feasibility remain important considerations. These findings establish that physical isolation, passive heat management, and alternative suppression agents are scientifically relevant research directions; however, they do not yet establish a universally effective, low-cost, waterless firebreak system suitable for heterogeneous tropical peatlands.

The disruptive novelty proposed in this study is to shift peatland fire control from the application of consumable extinguishing agents toward an adaptive, material-efficient firebreak strategy guided by subsurface thermal information. The proposed system, provisionally designated GAMBUT-LOCK, integrates temperature-based hotspot localization, mechanically formed barrier pathways, locally sourced mineral materials, and repeated thermal verification within a unified intervention framework. Rather than constructing uniform firebreaks across an entire affected area, the concept seeks to identify critical locations where a strategically positioned barrier may interrupt smoldering propagation while minimizing excavation, material consumption, and operational expenditure. The use of locally available mineral resources is intended to reduce dependence on transported suppression agents and specialized consumables, while the adaptive design aims to accommodate variations in peat depth, density, moisture content, and combustion behavior. Importantly, the novelty does not reside in the general use of mineral barriers or thermal sensors individually, but in the proposed integration and experimentally testable decision process connecting hotspot identification, barrier configuration, and post-intervention verification. The novelty of this integration must ultimately be established through systematic comparison with existing technologies and prior patent disclosures.

Accordingly, this study aims to design and experimentally validate a low-cost adaptive firebreak for waterless peatland fire control and reignition prevention using locally sourced materials. The research will

characterize candidate mineral materials, develop a prototype for controlled barrier formation, and evaluate its performance against appropriate untreated and conventional firebreak controls under reproducible laboratory conditions. Key performance indicators will include the probability of smoldering-front interruption, subsurface temperature evolution, residual combustion, reignition incidence, material consumption, intervention time, and estimated operational cost. Experimental trials will examine how peat moisture, bulk density, layer thickness, and barrier configuration influence suppression performance and the potential for fire propagation around or beneath the barrier. The central hypothesis is that an appropriately configured mineral barrier, positioned using subsurface thermal information, can reduce smoldering propagation and material requirements relative to a conventional non-adaptive barrier under specified experimental conditions. By establishing the relationships between barrier geometry, peat properties, thermal behavior, and suppression outcomes, this research seeks to provide an evidence-based foundation for a practical, affordable, and potentially patentable technology for tropical peatland fire management. The study will also identify the limitations of waterless physical isolation, recognizing that interruption of fire propagation does not necessarily guarantee complete extinguishment of residual smoldering zones.

LITERATURE REVIEW

Characteristics and Challenges of Peatland Fire Suppression

Peatland fires present a distinctive environmental challenge because combustion can persist beneath the soil surface, even after visible flames have disappeared. Unlike conventional vegetation fires, which primarily consume exposed fuels, peat fires can propagate through layers of organic material and remain active under limited oxygen availability. Their behavior is influenced by peat composition, moisture conditions, soil structure, and the availability of oxygen within the subsurface environment. These characteristics make detection and suppression particularly difficult in tropical peatlands, where drainage, prolonged dry periods, and land-use changes can increase the vulnerability of organic soils to combustion. Smoldering fires can continue to produce smoke and release stored carbon while remaining difficult to locate using visual observation alone. Consequently, effective peatland fire management requires approaches that address the continuity of combustible material, subsurface heat retention, and the possibility of reignition rather than relying exclusively on the disappearance of surface flames.

Conventional peatland firefighting frequently depends on water-based suppression, which can provide cooling and reduce combustion temperatures when sufficient water reaches the active burning zone (Escobar & Hübinger, 2026). However, transporting water into remote peatlands can be difficult, particularly where access roads are limited and water sources are distant from affected locations. Water may also infiltrate unevenly through heterogeneous peat layers, making it difficult to ensure that all active combustion zones receive adequate cooling. These constraints can increase the operational burden on firefighting teams and complicate efforts to maintain suppression over extended periods. For resource-constrained fire management, particularly in rural and remote areas of Indonesia, these limitations motivate the exploration of alternative strategies that reduce dependence on transported water and expensive consumable materials. A promising direction is to focus on localized intervention, physical interruption of combustion pathways, and the efficient use of materials that are readily available near the affected area.

Low-Cost and Locally Sourced Materials for Firebreak Development

The use of locally sourced mineral materials offers a potential pathway toward more affordable peatland fire management (Yunus et al., 2025). Depending on local geological conditions, candidate materials may include suitable mineral soil, clay-rich earth, and other noncombustible materials available near peatland areas. Their potential value lies in reducing dependence on specialized suppression agents and minimizing transportation requirements. Nevertheless, local availability alone does not establish suitability. Material selection must consider thermal behavior, physical stability, compatibility with surrounding peat, and the possibility of undesirable environmental effects. A material that is noncombustible may still conduct heat or leave pathways through which smoldering combustion can continue. Therefore, low-cost material selection should be based on practical performance rather than price alone.

Physical firebreaks provide a relevant foundation for this approach. (Lin et al., 2021) investigated the use of firebreaks to interrupt smoldering peat fires under laboratory conditions, demonstrating that their effectiveness depends on characteristics such as peat-layer thickness and moisture conditions. Their findings suggest that modifying the continuity of combustible material can provide an alternative to relying exclusively on direct application of extinguishing agents. However, the performance of a firebreak depends on its configuration and the characteristics of the surrounding peat. A barrier that is effective in one experimental setting may not provide equivalent protection in a different peat profile. This limitation supports further

investigation into firebreak designs that are simple to construct, economical to maintain, and adaptable to variations in local peatland conditions.

Physical Firebreaks as an Alternative to Resource-Intensive Suppression

Physical firebreaks offer a different approach to peatland fire control by attempting to interrupt the pathways through which smoldering combustion propagates. Rather than cooling the entire affected area, this strategy seeks to isolate the burning zone from adjacent combustible peat. When appropriately designed, a firebreak may reduce the need for extensive application of suppression materials. This makes physical isolation particularly relevant to low-cost technologies intended for locations where water transportation and specialized equipment impose significant operational burdens.

Nevertheless, underground fire propagation presents important limitations. Smoldering combustion may continue beneath a shallow barrier or travel around its edges through connected organic layers. The effectiveness of a physical barrier therefore depends on its relationship to the depth and structure of the burning peat. Research by (Lin et al., 2021) provides an experimental basis for understanding how firebreak characteristics influence the interruption of smoldering propagation. More recently, (Musa et al., 2026) explored buried heat pipes as a means of modifying subsurface heat transfer and controlling peat fire propagation. Although this approach demonstrates the potential of engineered subsurface interventions, specialized thermal components may introduce additional fabrication and installation requirements. For applications emphasizing affordability, a simpler mineral-based barrier may offer a complementary research direction, provided its effectiveness can be demonstrated under controlled conditions.

Adaptive Firebreaks and Practical Subsurface Monitoring

A major challenge in peatland fire management is determining where intervention is necessary and whether the intervention has actually controlled the fire (Jefferson et al., 2020). Surface observations alone may be insufficient because residual heat and combustion can remain beneath apparently extinguished ground. Subsurface temperature monitoring can help identify locations that require further investigation and provide information about changes in thermal conditions after an intervention. However, sensor systems can introduce additional costs, maintenance requirements, and operational complexity if they depend on extensive instrumentation or specialized electronic components.

A low-cost alternative is to investigate a limited set of reusable temperature probes and a straightforward monitoring procedure. Rather than requiring continuous high-resolution sensing across an entire landscape, the system could prioritize measurements at selected locations where subsurface heating is suspected. These observations could guide the placement of physical barriers and help determine whether further inspection is necessary. Such an approach would preserve the practical benefits of thermal information while limiting dependence on expensive sensing infrastructure. However, temperature measurements must be interpreted cautiously because a temporary decline in measured temperature does not necessarily establish that smoldering combustion has ceased. Repeated observations and appropriate inspection procedures are therefore important components of a reliable verification strategy.

Adaptive firebreak design extends this principle by adjusting the placement and configuration of a barrier to the observed characteristics of the affected area. Instead of constructing uniform barriers across large sections of peatland, an adaptive approach would seek to intervene at locations where a barrier is most likely to interrupt combustion propagation. The intended benefits include reduced excavation, lower material consumption, and simpler deployment. These benefits remain research objectives rather than established outcomes and must be evaluated against conventional firebreak configurations.

Research Gap and Proposed Low-Cost Innovation

Existing research demonstrates several possible approaches to peatland fire suppression, including water-based cooling, alternative extinguishing agents, physical firebreaks, and engineered subsurface heat management (Lin & Huang, 2020). Each approach offers potential advantages but also introduces practical trade-offs. Specialized suppression agents may require substantial material inputs or difficult transportation arrangements, while engineered heat-transfer systems may involve additional components and installation requirements. Physical firebreaks can reduce dependence on direct suppression materials, but their effectiveness depends on the configuration of the barrier and the characteristics of the burning peat. These considerations indicate a need for further research into practical, low-cost firebreak technologies that prioritize locally available materials and straightforward construction methods.

The proposed GAMBUT-LOCK concept addresses this opportunity through an adaptive mineral firebreak intended to interrupt subsurface peat fire propagation without relying on water as the primary suppression agent. Its central design principle is to combine locally sourced mineral material, a mechanically

simple barrier-forming mechanism, and basic subsurface temperature monitoring. The system is intended to minimize dependence on expensive consumables, reduce unnecessary excavation, and provide a practical method for identifying locations where additional intervention may be required. Unlike approaches that depend primarily on specialized cooling agents or complex thermal infrastructure, the proposed concept emphasizes material accessibility, mechanical simplicity, and ease of maintenance. Its potential novelty lies in the integration of these elements into an adaptive intervention strategy rather than in the individual use of mineral materials or temperature sensors.

The present study therefore focuses on the design and experimental evaluation of a low-cost adaptive firebreak for waterless peatland fire control and reignition prevention. The research will investigate the suitability of locally sourced mineral materials, examine how barrier configurations influence the interruption of smoldering propagation, and assess the usefulness of repeated temperature monitoring for identifying residual combustion. Particular attention will be given to practical considerations, including ease of construction, material availability, maintenance requirements, and potential environmental disturbance. By prioritizing accessible materials and uncomplicated engineering principles, the study seeks to establish a foundation for a potentially affordable peatland fire-control technology suitable for further development and field evaluation.

METHODOLOGY

Research Design

This study will employ a qualitative, design-oriented experimental approach to develop and evaluate a low-cost adaptive firebreak for waterless peatland fire control and reignition prevention (Judijanto, 2026). The research will focus on understanding how locally sourced mineral materials, simple barrier configurations, and subsurface temperature monitoring can be integrated into a practical firebreak system. Rather than prioritizing complex automation or expensive suppression agents, the study will emphasize material accessibility, mechanical simplicity, ease of maintenance, and suitability for resource-constrained peatland environments.

The research will combine a review of relevant literature, characterization of candidate materials, iterative prototype development, controlled laboratory observations, and qualitative evaluation of operational feasibility. Laboratory experiments will be used to examine the behavior of smoldering peat and the effectiveness of proposed barrier configurations under controlled conditions. Observations will focus on whether combustion continues toward or beyond the barrier, whether residual heat remains within the treated area, and whether signs of renewed combustion appear during subsequent monitoring. These observations will inform successive design modifications and the development of a practical prototype.

Although the study is primarily qualitative, basic measurements of temperature, material consumption, intervention time, and prototype cost may be recorded to support the interpretation of experimental observations. These measurements will serve as descriptive engineering evidence rather than as the basis for an extensive statistical modeling framework.

Research Location and Material Selection

The research will be conducted in two stages: preliminary material assessment and controlled laboratory testing (Hu, 2008). Candidate materials will be identified based on their availability in peatland regions of Indonesia, particularly areas where suitable mineral soil can be sourced locally. Potential materials may include mineral soil with low organic content and clay-rich soil, subject to preliminary assessment of their physical properties and environmental suitability.

Material selection will consider practical availability, ease of transportation, handling requirements, physical stability, and compatibility with the surrounding peat environment. Materials that contain substantial combustible organic matter or potentially harmful contaminants will be excluded. The selected materials will then be examined to determine whether they can form a stable barrier without introducing unacceptable thermal or ecological risks.

Local availability will be treated as an initial selection criterion rather than proof of effectiveness. Each candidate material must demonstrate appropriate performance under controlled conditions before being considered for incorporation into the prototype.

Development of the GAMBUT-LOCK Prototype

The prototype will be developed as a mechanically simple firebreak system consisting of three principal components: a barrier-forming mechanism, a mineral barrier material, and a basic subsurface monitoring system.

The barrier-forming mechanism will be designed to create a localized interruption in the continuity of combustible peat. Its configuration will prioritize ease of fabrication, minimal excavation, and the ability to operate under conditions commonly encountered in peatland environments. The mineral barrier will serve as the principal physical component intended to restrict the propagation of smoldering combustion.

The monitoring component will use reusable temperature probes positioned at selected locations around the experimental barrier. Temperature observations will help identify persistent heating and possible changes in combustion behavior. A simple data-recording interface may be incorporated to document observations and support decisions about whether further inspection is necessary.

The prototype will initially be operated manually or semi-automatically to minimize development costs and technical complexity. Advanced sensors, robotics, and artificial intelligence will only be considered in subsequent development if experimental findings demonstrate a clear practical benefit.

Experimental Procedure

The experimental procedure will be organized into sequential activities designed to evaluate the feasibility of the proposed waterless firebreak. First, the selected peat and mineral materials will be characterized under controlled laboratory conditions. Their physical properties, moisture conditions, and suitability for experimental use will be documented. The experimental peat will be prepared consistently to reduce unintended differences between test conditions.

Second, a baseline condition will be established to document the behavior of smoldering peat without the proposed intervention. This will provide a reference for interpreting subsequent observations. Additional comparison conditions will include an appropriate conventional physical firebreak and alternative mineral barrier configurations, where feasible.

Third, the GAMBUT-LOCK prototype will be installed in a controlled peat-fire test arrangement by trained personnel using an approved experimental protocol. The experiments will investigate whether the proposed barrier can interrupt the propagation of smoldering combustion and whether its configuration influences the persistence of residual heat. All combustion tests will take place in a suitable laboratory facility equipped with fire containment, smoke extraction, gas monitoring, and emergency suppression provisions.

Fourth, temperature observations and visual evidence will be documented during and after the intervention. Particular attention will be given to signs of continued combustion near the barrier, propagation around or beneath the barrier, and the reappearance of heating after an initial decline. The observation period will be defined in advance and applied consistently across comparison conditions.

Finally, the experimental findings will be used to identify design limitations and guide prototype refinement. Modifications may address barrier stability, ease of construction, material requirements, or the positioning of monitoring points. No configuration will be considered successful solely because visible flames have disappeared.

Qualitative Evaluation of Firebreak Performance

The performance of the proposed firebreak will be evaluated primarily through structured observation and comparison. The assessment will examine four main dimensions. Combustion interruption will be assessed by observing whether smoldering propagation continues toward, beneath, or beyond the barrier. Particular attention will be given to possible bypass pathways and residual combustion within the treated zone.

Thermal behavior will be evaluated through repeated observations of temperature changes at selected locations. These observations will help distinguish temporary cooling from more sustained stabilization, while recognizing that temperature measurements alone cannot conclusively establish complete extinguishment.

Operational practicality will be assessed by examining the simplicity of installation, the amount of excavation required, the availability of materials, the ease of handling, and the maintenance requirements of the prototype.

Economic and environmental feasibility will be assessed by considering material consumption, fabrication requirements, operational effort, and potential disturbance to peat structure and surrounding vegetation. Particular attention will be given to whether locally sourced materials can reduce transportation and procurement burdens without compromising safety or firebreak performance.

These dimensions will provide a qualitative basis for determining whether the proposed technology merits further development.

Data Collection and Documentation

Data will be collected through laboratory observation sheets, temperature records, photographs, prototype design documentation, and records of material use and operational procedures. The observation sheets will document the initial experimental conditions, barrier configuration, observed combustion behavior, changes in temperature, signs of continued propagation, and any indication of renewed combustion during follow-up monitoring. Photographic documentation will be used to record the prototype, material characteristics, barrier integrity, and relevant experimental observations.

Descriptive information about material costs, fabrication requirements, and intervention time will also be recorded. These records will support the qualitative assessment of whether the proposed system offers practical advantages over alternative configurations.

All observations will be documented using consistent procedures. Deviations from the experimental protocol, sensor malfunctions, and ambiguous observations will be recorded explicitly to prevent uncertain results from being interpreted as evidence of successful suppression.

Data Analysis

The collected information will be analyzed using qualitative descriptive and comparative analysis. Observations from the baseline condition, conventional firebreaks, and experimental GAMBUT-LOCK configurations will be organized according to the main evaluation dimensions.

The analysis will identify recurring patterns in combustion propagation, barrier performance, residual heating, operational difficulties, and material requirements. Differences between configurations will be interpreted in relation to their physical characteristics and the conditions under which the observations were obtained.

The analysis will also identify failure mechanisms, including combustion bypassing the barrier, insufficient barrier stability, persistent heating, and possible reignition. These findings will be used to explain why particular configurations appear more or less suitable and to determine which modifications should be prioritized.

Where basic measurements are available, descriptive comparisons of temperature trends, material consumption, and intervention time will complement the qualitative findings. These measurements will not be used to claim statistical superiority unless the experimental design and collected data adequately support such conclusions.

Reliability, Validity, and Experimental Safety

The reliability of the findings will be supported by consistent experimental procedures, documented material characteristics, repeated observations, and systematic recording of deviations. Where feasible, important experimental conditions will be repeated to determine whether the observed behavior is consistent.

The validity of the evaluation will be strengthened by using appropriate comparison conditions and by distinguishing between interruption of fire propagation and complete extinguishment of the combustion source. Temperature monitoring will be combined with other relevant observations, and uncertain findings will be reported transparently.

Experimental safety will be treated as a prerequisite for all combustion testing. Tests will be conducted only in an appropriately equipped facility under the supervision of personnel experienced in fire research. Smoke, carbon monoxide, heat exposure, and the possibility of renewed combustion will be managed through an approved safety protocol. Field demonstrations will not be undertaken until laboratory performance and operational safety have been adequately assessed.

Expected Methodological Contribution

The methodology is intended to establish whether a low-cost adaptive mineral firebreak can provide a practical means of interrupting subsurface peat-fire propagation without relying on water as the primary suppression agent. Its principal contribution will be the systematic development and evaluation of a prototype that emphasizes locally sourced materials, simple mechanical construction, and basic thermal monitoring.

The findings will provide an initial evidence base for improving the design, identifying operational limitations, and determining whether more extensive experimental validation is justified. The resulting technical documentation may also support subsequent patent assessment, subject to a separate examination of novelty, inventive step, and existing patent disclosures.

Importantly, the proposed methodology evaluates a research concept rather than assuming that the technology is already effective. Its success will depend on whether controlled experiments demonstrate reliable

interruption of smoldering propagation, acceptable material requirements, and a credible pathway toward affordable and environmentally responsible application in tropical peatlands (Renaldo et al., 2022).

RESULTS AND DISCUSSION

4.1. Suitability of Locally Sourced Mineral Materials

The initial material assessment is expected to identify locally available mineral soils as potential candidates for constructing a low-cost peatland firebreak (Dabros et al., 2025). Their principal advantage is the possibility of reducing dependence on specialized extinguishing agents and minimizing material transportation requirements. Materials obtained near peatland areas may also simplify procurement and replacement during maintenance. Nevertheless, local availability should not be interpreted as evidence of firebreak effectiveness. The suitability of each candidate will depend on its physical stability, thermal properties, organic content, and compatibility with the surrounding peat environment.

The most important consideration is whether the selected material can create a sufficiently effective interruption in the continuity of combustible peat. A mineral material may resist combustion while still allowing heat to pass through it or enabling smoldering to continue beneath an inadequately constructed barrier. Consequently, the material assessment must consider the behavior of the complete barrier system rather than the noncombustibility of the material in isolation. The expected contribution of this investigation is to establish a practical basis for selecting locally sourced materials that balance affordability, ease of handling, and potential fire-containment performance.

From a low-cost engineering perspective, the preferred material will not necessarily be the cheapest available soil. Instead, it will be the material that provides an acceptable combination of barrier stability, practical availability, low installation requirements, and demonstrated interruption of smoldering propagation. This distinction is important because a low purchase price may provide little economic benefit if the material requires extensive excavation or repeated installation.

4.2. Performance of the Adaptive Mineral Firebreak

The proposed GAMBUT-LOCK system is intended to interrupt subsurface fire propagation by combining a mechanically formed barrier with targeted intervention. Compared with uniform barrier construction, an adaptive approach may offer practical advantages by directing intervention toward locations where subsurface heating indicates a potential propagation pathway. This strategy could reduce unnecessary excavation and avoid the indiscriminate use of material across unaffected areas.

The experimental evaluation will determine whether the proposed configuration can interrupt smoldering propagation under controlled conditions (Musa et al., 2026). Particular attention will be given to whether combustion continues beneath the barrier, moves around its edges, or persists within the isolated burning zone. These observations are essential because an apparently intact surface barrier may not prevent underground propagation if combustible material remains connected beneath it.

If the adaptive configuration demonstrates more reliable interruption than the comparison conditions, the result would support further development of targeted physical isolation as a complementary method for peatland fire management. Conversely, if combustion repeatedly bypasses the barrier, the findings would indicate that the barrier geometry, placement, or interaction with the peat profile requires redesign. Such outcomes would remain valuable because they would identify the physical limitations of the proposed concept rather than simply evaluating its apparent surface performance.

The principal research question is therefore not whether mineral barriers can be constructed, but whether an adaptive barrier can provide reliable containment while reducing the material and labor requirements associated with conventional intervention.

4.3. Role of Subsurface Temperature Monitoring

Subsurface temperature monitoring is expected to support the identification of locations requiring intervention and the assessment of conditions following barrier construction (Shokri et al., 2026). Repeated temperature observations can help distinguish sustained thermal stabilization from temporary cooling and can reveal locations where additional investigation may be necessary.

The proposed monitoring system emphasizes reusable temperature probes and straightforward data recording rather than expensive, continuously operating sensor networks. This design choice is intended to preserve the practical benefits of subsurface monitoring while limiting hardware costs, maintenance demands, and technical complexity.

However, temperature measurements have inherent limitations. A sensor may fail to detect residual combustion located beyond its immediate measurement area, while a declining temperature at one location may coexist with continued smoldering elsewhere. Therefore, thermal observations must be interpreted alongside physical inspection, observations of propagation, and repeated monitoring over a predefined period.

The value of the monitoring component will ultimately depend on whether it improves intervention decisions sufficiently to justify its additional cost. If simple temperature probes provide adequate information for identifying residual heating and guiding follow-up inspection, they may offer a more accessible solution than complex sensor systems. If their observations are inconsistent or insufficiently informative, additional sensing methods may be required.

4.4. Reignition Prevention and Long-Term Containment

Reignition prevention is a central consideration in evaluating waterless peatland fire-control technologies (Carmenta et al., 2021). The disappearance of visible flames does not necessarily indicate that the underlying combustible material has been extinguished. Residual heat may persist within the peat, and smoldering may continue in locations that are not directly monitored.

GAMBUT-LOCK therefore incorporates repeated thermal verification as part of the proposed intervention process. The purpose is to determine whether the firebreak continues to interrupt propagation and whether evidence of residual or renewed combustion appears during follow-up observation. This approach treats verification as an integral part of suppression rather than as a separate activity performed only after the intervention has ended.

The experimental assessment should distinguish between three outcomes: interruption of propagation beyond the barrier, persistence of combustion within the treated area, and renewed propagation during the observation period. These outcomes have different implications for operational success. A barrier may prevent fire from spreading into adjacent peat while leaving an active source that still requires additional treatment.

Accordingly, the system should not be described as having completely extinguished a fire merely because no propagation is observed beyond the barrier. A defensible claim of successful suppression requires evidence that the original combustion source has also been extinguished or has been managed through an appropriate additional intervention. This distinction is particularly important when evaluating the proposed technology for future field deployment.

4.5. Low-Cost Engineering and Operational Feasibility

The economic rationale for GAMBUT-LOCK rests on three principal design choices: using locally sourced mineral materials, minimizing unnecessary excavation, and employing a mechanically simple construction system. These choices are intended to reduce dependence on specialized suppression consumables and complex equipment.

Unlike approaches that rely heavily on dry ice, cryogenic agents, or specialized heat-transfer components, the proposed system seeks to use material that can potentially be sourced near the intervention area (Liu et al., 2026). Its economic feasibility will nevertheless depend on the complete cost of operation, including material collection, transportation, labor, equipment fabrication, maintenance, and repeated inspection.

A locally sourced material may be inexpensive at the point of collection but costly to transport across difficult terrain. Similarly, a simple barrier may require extensive manual labor if its installation process is inefficient. Consequently, the assessment must consider the total operational requirements rather than comparing material prices alone.

The prototype should be evaluated against conventional physical firebreaks using consistent cost categories. Relevant considerations include the amount of material required, time needed to construct the barrier, ease of equipment transport, frequency of maintenance, and the additional labor required to investigate residual combustion.

If the adaptive system achieves reliable containment with less excavation and material use, it could offer a practical economic advantage. However, such an advantage must be established through actual prototype measurements and comparative cost records rather than inferred from the use of inexpensive materials alone.

4.6. Environmental Implications

The proposed use of locally sourced mineral materials may reduce the logistical burden associated with transporting specialized suppression agents (Firoozi et al., 2025). Nevertheless, environmental suitability must be considered alongside economic feasibility. Excavation can disturb peat structure, alter local drainage, damage vegetation, and introduce material from outside the immediate ecosystem.

The design should therefore prioritize localized intervention and the minimum disturbance necessary to construct an effective barrier. Candidate materials should be assessed for contamination risks, compatibility with the surrounding soil, and potential effects on local hydrology. Material sourcing should also avoid creating additional environmental damage at extraction locations.

These considerations are especially important in tropical peatlands, where soil structure and hydrological conditions contribute to ecosystem stability. A firebreak that suppresses combustion but causes substantial secondary damage may not provide a satisfactory long-term solution.

The proposed system should therefore be evaluated as an environmental engineering intervention, with effectiveness defined not only by its ability to interrupt fire propagation but also by its material requirements and ecological consequences.

4.7. Comparison with Existing Suppression Approaches

The proposed technology differs conceptually from conventional water-based suppression and alternative extinguishing agents because its principal intervention mechanism is physical interruption of subsurface fire propagation (Renaldo et al., 2024).

Approach	Principal mechanism	Main practical consideration
Water-based suppression	Cooling and wetting of combustible peat	Water availability, transport, and delivery to subsurface zones
Dry ice or cryogenic agents	Cooling and, depending on the agent, modification of local oxygen conditions	Consumable requirements, handling, and logistics
Buried heat pipes	Modification of subsurface heat transfer	Component design, installation, and material costs
Conventional physical firebreak	Interruption of combustible continuity	Barrier geometry, excavation, and potential bypass pathways
Proposed GAMBUT-LOCK	Adaptive mineral barrier guided by subsurface thermal observations	Effectiveness, construction effort, monitoring reliability, and total operating cost

This comparison identifies the intended positioning of GAMBUT-LOCK rather than demonstrating superior performance. Its distinguishing research proposition is the integration of locally sourced barrier material, targeted construction, and repeated verification within a low-cost intervention framework.

The system may be most relevant where the objective is to restrict the spread of a localized smoldering front and where extensive water delivery or specialized suppression agents are difficult to deploy. It should not be assumed to replace all existing firefighting methods, particularly when active combustion extends beyond the reach of the barrier or when the original burning zone requires direct extinguishment.



CONCLUSION

Conclusion

This study proposes GAMBUT-LOCK, a low-cost adaptive firebreak concept designed to support waterless peatland fire control through locally sourced mineral materials, mechanically simple barrier construction, and subsurface temperature monitoring. The proposed approach shifts the emphasis from extensive application of extinguishing agents toward targeted interruption of smoldering propagation. Its principal potential advantage lies in combining material accessibility, reduced dependence on water, and practical monitoring within an integrated firebreak system. However, its effectiveness in interrupting underground combustion, preventing reignition, and reducing operational costs remains to be established through controlled experiments. The proposed design should therefore be regarded as an engineering concept requiring experimental validation rather than a proven peatland fire suppression technology.

Implications

The proposed approach has potential implications for peatland fire management in Indonesia, particularly in remote areas where water transportation, specialized equipment, and operational resources may be limited. By prioritizing locally sourced materials and straightforward mechanical construction, GAMBUT-LOCK could provide an alternative framework for developing affordable firebreak technologies adapted to local conditions. Its integration of subsurface temperature monitoring also highlights the importance of distinguishing between the disappearance of visible flames and the continued presence of underground combustion.

From an engineering perspective, the concept encourages the development of fire-management technologies that balance suppression performance with material availability, operational simplicity, and environmental compatibility. For local communities and fire-management organizations, a successful system could potentially reduce dependence on specialized consumables and improve the targeting of interventions. Nevertheless, these benefits depend on demonstrating reliable fire containment, acceptable ecological impacts, and favorable total operating costs. The proposed system should complement, rather than replace, established firefighting procedures until its performance and safety have been adequately validated.

Limitations

The principal limitation of the present study is that GAMBUT-LOCK remains a proposed prototype concept, and its performance has not yet been established through experimental results. Consequently, its effectiveness, economic advantages, and ability to prevent reignition cannot currently be confirmed. The suitability of locally sourced mineral materials may also vary according to their composition, thermal properties, physical stability, and environmental compatibility.

Furthermore, laboratory experiments may not fully represent the heterogeneous conditions encountered in natural peatlands. Variations in peat depth, moisture, density, root structures, and underground combustion pathways may influence barrier performance. Temperature monitoring also has limitations because localized measurements may not detect residual combustion occurring outside the monitored area. Finally, constructing a physical barrier does not necessarily extinguish the original burning zone. These limitations require careful consideration when interpreting future experimental findings and determining the potential operational scope of the technology.

Recommendations

Future development should prioritize controlled laboratory experiments to establish whether the proposed mineral barrier can reliably interrupt smoldering propagation under different peat conditions. Candidate materials should be evaluated for availability, thermal behavior, physical stability, and environmental suitability before being incorporated into the prototype. Experimental comparisons should include untreated peat and appropriate conventional firebreak configurations to determine whether adaptive barrier placement provides meaningful practical advantages.

The prototype should emphasize mechanical simplicity, minimal excavation, reusable monitoring equipment, and locally available materials. Performance evaluation should consider combustion interruption, residual heating, reignition, material consumption, installation requirements, and total operational cost. A predefined verification protocol should be used to distinguish successful containment from complete extinguishment. Field demonstrations should only proceed after laboratory testing establishes an acceptable level of effectiveness and safety. In parallel, a systematic patent search should be undertaken before disclosing detailed technical configurations intended for intellectual property protection.

Future Research

Future research should extend the proposed concept through five complementary directions. First, material-focused investigations should identify locally available mineral materials that provide suitable barrier stability and thermal performance without causing unacceptable environmental disturbance. Second, engineering studies should investigate how barrier geometry, placement, and installation methods influence the interruption of subsurface combustion. Third, monitoring research should examine whether a simple network of reusable temperature probes can identify residual heating and support practical intervention decisions without introducing excessive costs.

Fourth, comparative economic and environmental assessments should determine whether the proposed system offers advantages over conventional physical firebreaks and selected suppression alternatives. These assessments should account for material sourcing, transportation, labor, maintenance, ecological disturbance, and the consequences of unsuccessful containment. Finally, field-oriented research should evaluate the technology under representative tropical peatland conditions after laboratory performance and safety have been demonstrated.

An additional research direction is the development of a semi-automated decision-support system that uses temperature observations to guide barrier placement and subsequent inspection. Such a system should initially prioritize transparent, rule-based decisions rather than complex artificial intelligence, allowing its operation to remain affordable, interpretable, and maintainable in resource-constrained settings.

Ultimately, the future development of GAMBUT-LOCK should be guided by experimental evidence demonstrating whether an adaptive, mineral-based firebreak can provide reliable containment at an acceptable cost. Establishing this evidence would provide the foundation for assessing its practical value, environmental suitability, and potential patentability as a technology for tropical peatland fire management.

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