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Research Article

FORMULATION OF ECO-FRIENDLY PALM OIL SURFACTANT FOAM FOR PEATLAND FIRE SUPPRESSION IN KALIMANTAN

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Abstract

Peatland fires in Kalimantan persist as deep, flameless smouldering fronts that resist suppression with water alone because dry peat is hydrophobic, while conventional fluorinated foams leave persistent per- and polyfluoroalkyl substances (PFAS) in sensitive wetland ecosystems. This study aims to formulate an environmentally friendly foam fire-extinguishing agent based on palm oil-derived plant-based surfactants for peatland fire suppression. A systematic integrative literature review combined with conceptual chemical process design was employed, synthesising 49 peer-reviewed and institutional sources on peat fire behaviour, surfactant science, palm oleochemical processing, and fluorine-free foam performance. The results show that soap-based agents applied at 1 vol% reduced the water required to extinguish peat fires in Central Kalimantan field trials by 42–76%, shortened suppression time by about 60%, accelerated infiltration into hydrophobic peat by up to tenfold, and prevented re-ignition without impairing vegetation recovery. The novelty of this work lies in an integrated process route and formulation framework that couples palm fatty acid soaps and methyl ester sulfonate with biodegradable stabilisers, chelators, and acidic-water tolerance criteria specific to Kalimantan peat. These findings imply that a locally produced, PFAS-free foam concentrate can strengthen peat fire mitigation while adding value to Indonesia's palm oil downstream industry.

Keywords: Firefighting foam, Methyl ester sulfonate, Palm oil surfactant, Peatland fire, Smouldering combustion

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INTRODUCTION

Peatland fires are among the most damaging environmental disasters affecting Indonesia, and Kalimantan is one of their principal theatres. Tropical peat forms over millennia as waterlogged plant material accumulates faster than it decomposes, and Indonesian peat swamps consequently store a very large share of the nation's terrestrial organic carbon. When drainage, land clearing, and prolonged dry seasons lower the water table, this carbon store becomes a fuel bed. The 1997 fire season provided the first quantitative demonstration of the scale of the problem: approximately 0.79 million hectares burned in Central Kalimantan alone, and peat combustion across Indonesia released an estimated 0.19–0.23 Gt of carbon into the atmosphere (Page et al., 2002). Subsequent global syntheses have confirmed that drained peatlands are highly vulnerable to fire and to irreversible carbon loss, because their organic soils tend to burn for weeks to months once ignited (Turetsky et al., 2015). The problem is therefore not episodic but structural, and it recurs whenever climatic and hydrological conditions align.

Recent evidence indicates that the character of Kalimantan's peat fires is shifting rather than disappearing. A two-decade analysis of burned peatlands in Kalimantan reported that, although the total peatland area burned in 2015–2021 decreased by 28.7% on average relative to earlier periods, the number of high-severity burn pixels increased by 12.1% and 13.4% compared with 2001–2007 and 2008–2014, respectively, and annual fire counts correlated strongly with precipitation anomalies ($R_S = -0.92$) and air temperature anomalies ($R_S = 0.88$) (Schmidt et al., 2024). Fires are thus becoming less widespread but more intense where they occur. Hydrology remains decisive: the 2023 El Niño, the second strongest of this century, produced much weaker hydrogen cyanide and carbon monoxide emissions from Indonesian peat fires than the comparable 2015 event because higher soil water content and precipitation limited the depth and intensity of burning (Bruno et al., 2026). These findings underline that the moisture state of peat governs both ignition and persistence, and that any suppression technology must ultimately be judged by its ability to deliver water into the burning peat matrix.

The human cost of peat fires is equally severe. Smouldering peat emits large quantities of fine particulate matter, carbon monoxide, and organic compounds, and is the principal driver of the transboundary haze episodes that recur across Equatorial Asia (Hu et al., 2018). Using a network of low-cost sensors and a regional air quality model, Graham et al. (2024) estimated that mean outdoor $PM_{2.5}$ in Central Kalimantan during the dry season reached 136 μg/m³, of which 90 μg/m³ was attributable to fires, and that about 1.62 million people in the province were exposed to unhealthy, very unhealthy, or dangerous air quality. The median indoor-to-outdoor $PM_{2.5}$ ratio of 1.01 in rural households indicated that homes offered little protection from smoke (Graham et al., 2024). Rapid and efficient suppression of peat fires is therefore a matter of public health as much as of carbon management.

The central technical difficulty is that peat fires are dominated by smouldering rather than flaming combustion. Smouldering is a slow, low-temperature, flameless form of combustion sustained by heterogeneous oxidation on the surface of a porous char, and it is far more persistent than flaming combustion even though its temperature, spread rate, and power are lower (Rein, 2009). Inverse modelling has resolved peat smouldering into drying, thermal pyrolysis, and oxidative decomposition steps, each with distinct kinetics and moisture sensitivity (Huang & Rein, 2014). Laboratory demonstrations show that smouldering temperature decreases with depth from roughly 550 °C to 350 °C at about 40 cm and then remains near 300 °C in deeper layers, where the fire can persist for weeks with limited oxygen and incomplete combustion (Qin et al., 2023). Ignition itself is strongly moisture-dependent: peat with a moisture content below 35% always ignites from a glowing firebrand, ignition between 35% and 85% requires wind, and peat above 85% cannot be ignited by a single laboratory firebrand (Lin et al., 2024).

These characteristics explain why water alone is an inefficient suppressant for peat fires. Most hot spots are located below the surface, and the relatively high surface tension of water impedes its penetration into the dry, hydrophobic peat matrix. Experimental work on Indonesian peat showed that water spray must flood the smouldering layer to achieve extinction (Ramadhan et al., 2017), and laboratory rainfall experiments indicated that a minimum intensity of 4 mm h^{-1} sustained for at least 5 h is required to suppress smouldering peat (Lin et al., 2020). The underlying phenomenon is soil water repellency, a well-documented property of dried organic soils in which hydrophobic organic coatings on particle surfaces prevent wetting and promote preferential flow (Doerr et al., 2000). As a consequence, large volumes of water are consumed during peat firefighting, and in remote areas of Kalimantan water supply and transport become the limiting factors of the entire suppression effort.

Surface-active agents offer a direct remedy for this limitation. Surfactants adsorb at the air–water and solid–water interfaces, lower surface tension, and reduce the contact angle of water on hydrophobic solids, thereby improving wetting and penetration (Rosen & Kunjappu, 2012). When aerated, surfactant solutions also form foams that adhere to fuel surfaces, retain water, release it gradually, and restrict oxygen access (Pugh, 1996). Santoso et al. (2021) showed that adding a plant-based wetting agent at a low concentration of 1% reduced the average suppression time of smouldering peat by 39% relative to pure water, while a 5% solution reduced it by 26%. Field experiments in Palangkaraya, Central Kalimantan, demonstrated that a 1 vol% soap-based agent halved the quantity of water required to extinguish peat fires and did not impair vegetation recovery after ten months (Kanyama et al., 2023). Subsequent experiments against prolonged 24 h simulated peat fires reported even greater water savings and the absence of re-ignition in soap-treated plots (Kanyama et al., 2025).

The choice of surfactant, however, carries significant environmental consequences. Aqueous film-forming foams (AFFF), which have dominated Class B firefighting since the 1970s, contain fluorinated surfactants whose persistence and bioaccumulation have been recognised for more than two decades (Moody & Field, 2000). Growing evidence of the health and environmental impacts of PFAS has triggered a global transition towards fluorine-free foams (F3), including a dedicated United States military specification for fluorine-free foam released in January 2023 (Ateia et al., 2023), national transition plans for aviation firefighting (Federal Aviation Administration, 2023), and continuing efforts to overcome the performance and qualification challenges of PFAS-free alternatives (Jahura et al., 2024; U.S. Government Accountability Office, 2024). Even non-fluorinated synthetic formulations are not automatically benign; ecotoxicological assays have shown that commercial AFFF samples are toxic to organisms at several trophic levels, including *Artemia salina*, *Lactuca sativa*, and *Eisenia fetida* (Rodrigues Junior et al., 2024). For peatlands, which are hydrologically connected wetlands with sensitive aquatic biota, a suppressant must therefore be both effective and readily biodegradable (Kalabokidis, 2000; Ying, 2006).

Indonesia possesses a strategic advantage in meeting this requirement. As the world's largest producer of palm oil, the country has abundant supplies of lauric, palmitic, and oleic fatty acids and their methyl esters, which are the natural precursors of soaps, methyl ester sulfonate (MES), and other oleochemical surfactants. Subekti et al. (2017) argued that palm oil is a promising raw material for environmentally friendly foaming agents for peat fires because of its availability, sustainability, and the ready degradability of the resulting foams in burned areas, and that such products would increase the value added by the palm oil downstream industry. Laboratory work has since produced palm fatty acid foaming agents (Rivai et al., 2017; Wahyuni & Dhora, 2019), formulated sodium laurate and potassium palmitate concentrates that save water during peat fire suppression (Subekti et al., 2019), and optimised formulas with mixture designs (Subekti et al., 2024). In parallel, MES synthesis from crude palm oil and waste cooking oil has advanced through sulfonation with bisulfite and metabisulfite reagents, microwave heating, and heterogeneous catalysts (Deli et al., 2025; Qadariyah et al., 2024).

Despite this progress, the literature remains fragmented across disciplines. Fire scientists have characterised peat smouldering and suppression hydraulics in detail, while chemical engineers and agro-industrial technologists have developed palm-based surfactants mostly for detergency, enhanced oil recovery, or generic foaming. The F3 literature, in turn, focuses predominantly on hydrocarbon pool fires and military qualification standards (Ateş et al., 2025; Sheng et al., 2020). Few studies have integrated these strands into a coherent process and formulation framework explicitly tailored to the acidic, low-hardness waters, hydrophobic substrates, and deep smouldering fronts typical of Kalimantan peatlands. Consequently, there is no consolidated reference that links feedstock selection, reaction route, formulation components, quality criteria, field proportioning, and environmental verification for a palm oil-derived peat fire foam.

Based on these considerations, this study aims to formulate an environmentally friendly foam fire-extinguishing agent based on palm oil-derived plant-based surfactants for peatland fire suppression in Kalimantan. Specifically, the study seeks to (1) characterise the physicochemical features of Kalimantan peat fires that determine suppressant requirements; (2) synthesise the empirical evidence on the performance of surfactant- and soap-based agents against peat fires; (3) evaluate candidate palm oil-derived surfactants and their production routes from a chemical and process engineering perspective; and (4) propose an integrated formulation framework, process flow, and evaluation matrix for a PFAS-free foam concentrate. The study is expected to provide a scientific basis for laboratory validation and pilot production, to support disaster management agencies in selecting safer suppressants, and to contribute to the diversification of palm oil downstream products.

RESEARCH METHOD

This study was designed as a qualitative-descriptive investigation that combined a systematic integrative literature review with conceptual chemical process design. The review approach was chosen because the research problem spans fire science, colloid and interface science, oleochemical processing, and environmental toxicology, and because a growing but scattered body of experimental evidence already exists that can be synthesised to guide formulation decisions before costly laboratory and field trials are undertaken. The conceptual design component translated the synthesised evidence into a process route and formulation framework, following the logic of chemical product design in which target properties are first defined and then matched with candidate ingredients and unit operations.

Research Design

The study adopted an integrative review design, which permits the inclusion of experimental, field, review, and techno-economic studies within a single analytical framework. The design comprised four sequential stages: problem formulation, literature search and selection, data extraction and evaluation, and synthesis into a formulation framework. Quantitative findings reported in the primary studies, such as water demand, suppression time, surface tension, and reaction yield, were extracted and compared descriptively; no new experimental data were generated in this study. The conceptual design stage followed a product-driven approach in which the functional requirements of a peat fire suppressant were specified first and then linked to surfactant classes, additives, and process routes.

Time and Place of Research

The review and design work were carried out in 2026. The geographical focus of the analysis was the peatland region of Kalimantan, Indonesia, with particular attention to Central Kalimantan, where most of the field suppression experiments relevant to this study were conducted. Literature describing peat fires and suppressants in other regions was included when it provided mechanistic or methodological insight transferable to tropical peat.

Research Target/Subject

The subjects of this study were scientific and technical documents addressing at least one of four thematic domains: (1) the behaviour and impacts of peat fires, particularly tropical and Indonesian peat; (2) the suppression of smouldering peat fires using water, wetting agents, or foams; (3) the synthesis and characterisation of palm oil-derived surfactants, including soaps and MES; and (4) the performance, regulation, and environmental safety of fluorine-free and environmentally friendly firefighting foams. Documents were selected purposively according to their relevance, scientific credibility, and the availability of verifiable bibliographic information. Priority was given to peer-reviewed journal articles published between 2023 and 2026 in order to capture the current state of research, while earlier seminal works were retained when they established foundational concepts, such as smouldering combustion theory, soil water repellency, surfactant and foam science, and the environmental implications of fluorinated surfactants. The final corpus consisted of 49 documents, of which 25 were published from 2023 onwards.

Research Procedure

The research procedure began with the formulation of guiding questions corresponding to the four objectives stated in the introduction. Literature was then searched in Google Scholar and in the online platforms of major publishers and indexing services, including ScienceDirect, SpringerLink, CSIRO Publishing, MDPI, the American Chemical Society, Wiley, J-STAGE, IOP Publishing, the Directory of Open Access Journals, and the Garuda portal of Indonesian journals, complemented by institutional repositories and government reports. Search strings combined terms such as "peat fire", "smouldering", "suppression", "wetting agent", "foaming agent", "palm oil", "fatty acid soap", "methyl ester sulfonate", "fluorine-free foam", "PFAS", and "biodegradability".

Retrieved documents were screened by title and abstract, and the remaining documents were assessed in full text against the inclusion criteria. Bibliographic details, including authors, year, title, source, volume, pages, and digital object identifiers, were verified against publisher or repository records before inclusion. Backward citation tracking was applied to key field studies to identify additional relevant work. Finally, the extracted findings were organised into thematic matrices that formed the basis of the results tables and the proposed formulation framework.

Instruments, and Data Collection Techniques

The principal instrument was a structured data extraction sheet developed by the authors. For each document, the sheet recorded the study type and scale, the fuel or substrate investigated, the suppressant or surfactant composition and dose, the operating conditions of synthesis where applicable, and the key quantitative outcomes, such as water demand per unit area or mass, suppression time, re-ignition behaviour, surface tension, foam stability, reaction yield, and ecotoxicological endpoints. Qualitative information on mechanisms, limitations, and recommendations was recorded in parallel. Data were collected through documentation, that is, by reading and coding the full texts of the selected documents.

Data Analysis Technique

Data were analysed using thematic synthesis and descriptive comparison. Thematic synthesis grouped the findings into the four domains defined above and identified convergent mechanisms, contradictory results, and knowledge gaps. Descriptive comparison was applied to quantitative outcomes, for example by expressing the water saving achieved by a surfactant-based agent as a percentage of the water required by plain water under the same conditions. The synthesised evidence was then mapped onto the functional requirements of a peat fire suppressant, namely wetting and penetration, foam formation and stability, cooling and oxygen

exclusion, tolerance to acidic and soft water, storage stability, biodegradability, and low toxicity, in order to derive the proposed process route, formulation ranges, and evaluation matrix. Because the analysis relied on published results obtained under heterogeneous conditions, comparisons were interpreted as indicative rather than statistically pooled.

RESULTS AND DISCUSSION

The results are organised according to the research objectives. They begin with the characteristics of Kalimantan peat fires that define suppressant requirements, followed by the interfacial and colloidal mechanisms through which surfactants improve suppression, the empirical performance of surfactant- and soap-based agents, and the palm oil-derived surfactant candidates and their production routes. On this basis, a formulation framework, process flow, and indicative mass and energy balance are proposed. The findings are then discussed in relation to environmental safety, alternative suppression strategies, techno-economic and logistical feasibility, a validation protocol, and the research gaps, novelty, and implications of the study.

Characteristics of Kalimantan Peat Fires and the Limits of Water-Only Suppression

The synthesis of fire science literature reveals five characteristics of tropical peat fires that directly determine the requirements for any suppressant. They are summarised in Table 1. The first is the dominance of smouldering combustion. Smouldering fronts propagate slowly but persistently through the porous peat matrix and can survive conditions, such as rainfall or limited oxygen, that would extinguish a flaming fire (Rein, 2009). The second characteristic is the vertical extent of burning. Smouldering penetrates tens of centimetres below the surface, with temperatures around 300–550 °C, and can continue for weeks in deep layers (Qin et al., 2023). Field measurements in Central Kalimantan recorded peat surface temperatures above 280 °C and underground temperatures of approximately 300 °C at depths of 2–4 cm during experimental fires, with an in-depth spread rate of about 1.2 cm/h (Kanyama et al., 2023).

The third characteristic is the strong dependence of ignition and spread on moisture. Peat with less than 35% moisture ignites reliably, whereas peat above 85% moisture resists ignition by a single firebrand (Lin et al., 2024), and the multistep kinetics of drying, pyrolysis, and oxidation are all moderated by the water content of the fuel (Huang & Rein, 2014). The fourth characteristic is the hydrophobicity of dried peat. Water drop penetration tests on Kalimantan peat recorded a penetration time of 102 s for groundwater compared with only 10 s for a 1 vol% soap-based solution (Kanyama et al., 2023), which is consistent with the general mechanism of soil water repellency in dried organic soils (Doerr et al., 2000). The fifth characteristic is the chemistry of available water. Groundwater used for firefighting at the Palangkaraya sites had a pH of 5.2–5.6 and a hardness of 0 ppm (Kanyama et al., 2023), whereas peat porewater is commonly more acidic. This chemistry affects the choice of surfactant, because fatty acid soaps are converted to insoluble free fatty acids under strongly acidic conditions and precipitate as metal soaps in hard water.

Table 1. Key Characteristics of Tropical Peat Fires Relevant to Suppressant Design

No.	Characteristic	Evidence Reported in the Literature	Implication for Agent Design
1	Smouldering-dominated combustion	Slow, flameless, low-temperature but highly persistent oxidation of porous char (Rein, 2009); multistep drying, pyrolysis, and oxidation kinetics (Huang & Rein, 2014)	Agent must cool the char and suppress oxidation over long periods rather than merely knock down flames

No.	Characteristic	Evidence Reported in the Literature	Implication for Agent Design
2	Deep, long-lasting burning	Temperatures of ~550 °C near the surface to ~300 °C below 40 cm; persistence for weeks (Qin et al., 2023); in-depth spread of ~1.2 cm/h in Kalimantan peat (Kanyama et al., 2023)	Solution must penetrate deeply; foam blanket should retain water and release it gradually
3	Moisture-controlled ignition	Peat below 35% moisture always ignites; above 85% resists ignition (Lin et al., 2024)	Raising and retaining moisture above the ignition threshold is a primary target
4	Hydrophobic dry peat	Water drop penetration of 102 s for water versus 10 s for 1 vol% soap solution (Kanyama et al., 2023); soil water repellency mechanisms (Doerr et al., 2000)	Low surface tension (≈30 mN/m) and good wetting are essential
5	Acidic, soft local water	Groundwater pH 5.2–5.6 and hardness 0 ppm in Palangkaraya (Kanyama et al., 2023)	Surfactant system must remain active in acidic water; chelators protect against occasional hardness

The implications of these characteristics for water-only suppression are clear. Laboratory studies show that suppression of smouldering peat is essentially a flooding process, in which the fluid must saturate the burning layer. Santoso et al. (2021) found that the volume of fluid contributing to suppression remained approximately constant at 5.7 ± 2.1 L per kg of peat regardless of flow rate and wetting agent concentration, suggesting that the agent acts thermally rather than chemically. Experiments on Indonesian peat likewise showed that water spray must reach and saturate the smouldering layer to stop its spread (Ramadhan et al., 2017), and simulated rainfall needed an intensity of at least 4 mm h^{-1} for five hours to achieve suppression (Lin et al., 2020). Alternative delivery methods, such as direct water injection into the peat layer, have been investigated at laboratory scale (Mulyasih et al., 2022), water-based compositions with additives have been shown to suppress both flaming combustion and the thermal decomposition of model forest and peat fuels (Zhdanova et al., 2023), and direct injection was deployed alongside water spray during the GAMBUT field experiment, in which emission factors were found to differ significantly between ignition, spread, and suppression stages (Hu et al., 2024). Collectively, these studies indicate that the efficiency of peat fire suppression is governed less by the total quantity of water applied than by the fraction of that water that actually infiltrates and remains in the burning zone.

From a chemical engineering standpoint, this observation reframes the problem as one of interfacial mass and heat transfer. Plain water applied to hydrophobic peat runs off or flows preferentially through cracks and macropores, bypassing much of the smouldering char. Each litre that fails to infiltrate represents not only wasted water but also additional transport and pumping effort in remote terrain. An effective additive should therefore increase the infiltration efficiency and residence time of water within the peat, which is precisely the function of wetting agents and foams.

Interfacial Mechanisms of Surfactant-Assisted Peat Fire Suppression

Surfactants improve peat fire suppression through four complementary mechanisms. The first is wetting. By adsorbing at the air–water interface, surfactant molecules reduce the surface

tension of water from about 72 mN/m to approximately 30 mN/m, and by adsorbing at the solid–water interface they reduce the contact angle on hydrophobic organic surfaces (Rosen & Kunjappu, 2012). The soap-based agent used in the Kalimantan field trials exhibited a surface tension of 31.1–31.2 mN/m at 1 vol%, compared with 72.2 mN/m for water (Kanyama et al., 2023, 2025). According to the Laplace and Washburn relations, a lower surface tension and contact angle decrease the capillary entry pressure into hydrophobic pores and accelerate infiltration, which explains the approximately tenfold reduction in penetration time reported for treated water (Kanyama et al., 2023).

The second mechanism is enhanced cooling. Once the solution penetrates the peat, its high latent heat of vaporisation removes heat from the smouldering char more uniformly. Field measurements showed that after the initial firefighting application the peat surface temperature fell to approximately 66 °C with the soap-based solution, compared with approximately 160 °C with water alone, and that hot spots above 150 °C were common in water-treated plots but nearly absent in soap-treated plots (Kanyama et al., 2023). The third mechanism is foam blanketing. Foams adhere to surfaces, retain liquid in their lamellae and Plateau borders, and drain slowly, providing a sustained supply of water and a physical barrier that restricts oxygen diffusion and the escape of flammable pyrolysis gases (Pugh, 1996). The stability of this blanket depends on drainage, coarsening, and film rupture, which can be controlled through surfactant structure, polymeric thickeners, and particles (Papagiannis et al., 2024; Zhao et al., 2024).

The fourth mechanism is the prevention of re-ignition. Because smouldering can persist beneath an apparently extinguished surface, re-ignition is a major operational problem. In 24 h simulated peat fires, water-treated plots at one site re-ignited the following day and required further firefighting, whereas soap-treated plots did not re-ignite (Kanyama et al., 2025). Laboratory foam suppression experiments on tropical peat also indicate that a foam layer can contribute to the extinction of smouldering combustion (Ratnasari et al., 2018). Taken together, these mechanisms show that the role of the surfactant is primarily physical: it does not chemically inhibit combustion reactions but improves the delivery, distribution, and retention of water. This interpretation is consistent with the thermal rather than chemical mode of action inferred by Santoso et al. (2021) and implies that formulation should prioritise wetting, foaming, and stability rather than radical-scavenging chemistry.

Colloidal Design Criteria: Critical Micelle Concentration, Krafft Point, and Foam Stability

Translating the interfacial mechanisms into a workable product requires attention to several colloidal parameters that are well established in surfactant science but rarely discussed explicitly in the peat fire literature. The first is the critical micelle concentration (CMC). Below the CMC, surface tension falls steeply with increasing surfactant concentration; above it, additional surfactant forms micelles and the surface tension approaches a plateau (Rosen & Kunjappu, 2012). The CMC therefore defines the minimum effective concentration of the diluted solution. In general, the CMC decreases as the hydrophobic chain lengthens and is lower for mixtures that exhibit synergistic interaction. For a peat fire agent, this means that a blend of medium-chain (C12) and long-chain (C16–C18) palm surfactants can reach the surface tension plateau at a lower total concentration than either component alone, which helps explain why a 1% solution performed as well as or better than a 5% solution in laboratory suppression tests (Santoso et al., 2021).

The second parameter is the Krafft point, the temperature below which the solubility of an ionic surfactant is too low for micelles to form. The Krafft point increases with chain length and saturation and is generally lower for potassium salts than for sodium salts (Rosen & Kunjappu, 2012). This has practical implications for palm-based soaps. Sodium palmitate and sodium stearate, which derive from the saturated fraction of palm oil, have limited solubility at ambient temperature, whereas potassium soaps and soaps of unsaturated oleic acid remain soluble. The good performance of sodium oleate reported by Wahyuni and Dhora (2019) and the use of

potassium laurate and potassium oleate in the field-tested agent (Kanyama et al., 2023) are consistent with this principle. Although the tropical climate of Kalimantan reduces the risk of crystallisation, concentrates may be stored in air-conditioned warehouses or transported at night, so a low Krafft point and the inclusion of glycol co-solvents remain advisable.

The third group of parameters concerns foam generation and stability. Foam expansion ratio, defined as the ratio of foam volume to the volume of solution, determines whether the foam behaves as a wet, penetrating foam or as a dry, insulating blanket. Low-expansion foams carry more liquid and are better suited to penetrating smouldering peat, while medium-expansion foams provide greater coverage and oxygen exclusion on the surface. Foam stability is governed by gravitational drainage of liquid through Plateau borders, gas diffusion between bubbles of different sizes (coarsening or disproportionation), and rupture of thin films (Pugh, 1996). Additives that increase bulk and surface viscosity, such as xanthan gum or cellulose derivatives, slow drainage, while particles that accumulate at interfaces and in Plateau borders reduce coarsening and increase foam half-life (Papagiannis et al., 2024). In fluorine-free foams for liquid fuels, the addition of low-carbon alcohols has been shown to block liquid channels and increase stability (Jia et al., 2024), and stronger foam stability, rather than film formation, has been identified as the main reason for superior extinguishing and burnback performance in some silicone–hydrocarbon systems (Sheng et al., 2020).

For peat applications, these criteria suggest a balanced design. The foam should be stable enough to remain on the surface for several minutes, supplying water to the upper peat layer and suppressing flaming of surface vegetation, but it should also drain readily so that the liquid penetrates into deeper smouldering layers. An excessively stable, dry foam could insulate the surface while allowing deep smouldering to continue unseen. Accordingly, the formulation framework proposed later in this article favours a modest level of stabiliser and recommends that field crews use low-expansion application for the initial attack on hot spots and medium-expansion application for perimeter protection and mop-up.

Performance Evidence of Soap- and Surfactant-Based Agents on Peat Fires

Table 2 summarises the quantitative performance of water and surfactant-based agents reported in laboratory and field studies of peat fires. The evidence is consistent across scales and research groups: adding a surfactant at low concentration reduces the water demand and suppression time, and in some cases prevents re-ignition.

Table 2. Reported Performance of Water and Surfactant-Based Agents in Peat Fire Suppression

No.	Study and Scale	Agent and Dose	Key Reported Outcome
1	Santoso et al. (2021); laboratory reactor, peat sample	Plant-based wetting agent at 0%, 1%, and 5% in water	Mean suppression time reduced by 39% (1%) and 26% (5%) versus water; constant fluid demand of 5.7 ± 2.1 L/kg peat
2	Kanyama et al. (2023); meso-scale field plots, 1.5 m × 1.5 m, Palangkaraya	Potassium laurate–oleate soap agent, 1 vol%	Water demand 4.7 L/m² versus 8.1 L/m² for groundwater; no additional firefighting required
3	Kanyama et al. (2023); large-scale natural peat, 7 m × 7 m, Palangkaraya	Same agent, 1 vol%, line proportioner	Water demand 3.6 L/m² versus 7.2 L/m²; surface temperature ~66 °C versus ~160 °C after initial attack; vegetation recovery equal to water after 10 months

No.	Study and Scale	Agent and Dose	Key Reported Outcome
4	Kanyama et al. (2025); 24 h simulated peat fires at two Central Kalimantan sites	Soap-based agent, 1 vol%	Water demand 3.8 and 7.4 L/m² versus 16.0 and 23.9 L/m²; time 11 and 8 min versus 29 and 21 min; no re-ignition in soap plots
5	Subekti et al. (2019); laboratory peat fire test	Palm-based concentrate of 15% sodium laurate and 3% potassium palmitate, dosed at 3.33 wt%	Fire extinguished with 9.89 wt% water saving and shorter suppression time than well water
6	Ratnasari et al. (2018); laboratory tropical peat	Foam suppression of smouldering combustion	Foam layer contributed to the extinction of smouldering tropical peat

The magnitude of water savings reported in the field is substantial. In the meso-scale and large-scale trials in Palangkaraya, the soap-based agent reduced the total water demand by 42% and 50%, respectively (Kanyama et al., 2023). Against prolonged 24 h fires, which represent deeper and more established smouldering, the reductions reached 76% and 69% at the two sites, and suppression time was shortened by approximately 60% (Kanyama et al., 2025). These data are visualised in Figure 1, which highlights that the relative advantage of the surfactant agent increases as the fire becomes more deeply established, presumably because deeper fires demand more effective penetration.

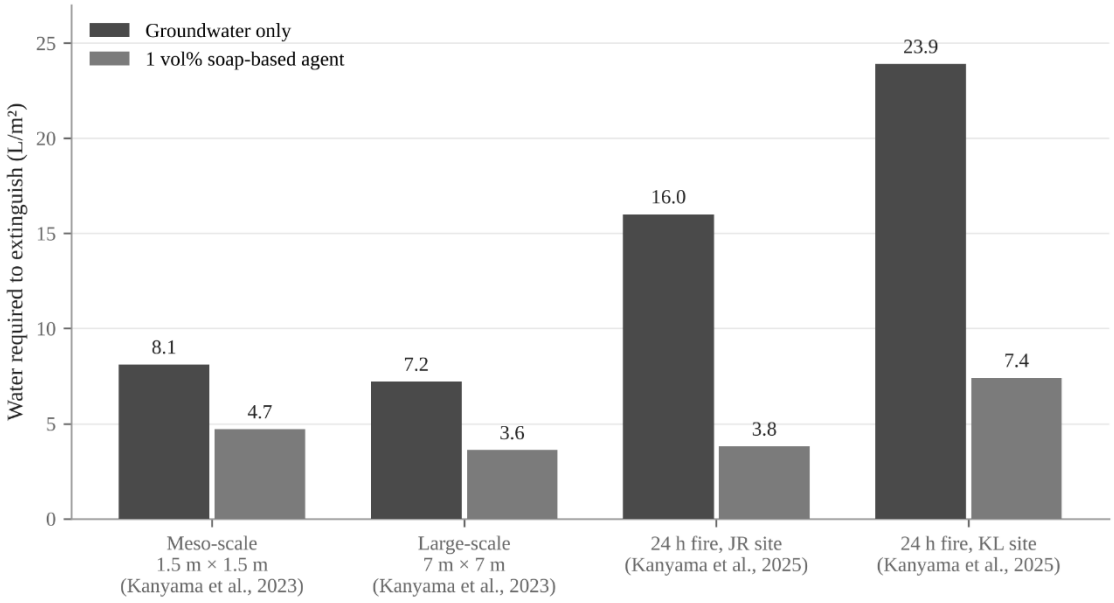


Figure 1. Water Required to Extinguish Peat Fires Using Groundwater and a 1 vol% Soap-Based Agent in Central Kalimantan Field Experiments (Data from Kanyama et al., 2023, 2025)

The laboratory results of Santoso et al. (2021) provide an important nuance. The 1% wetting agent outperformed the 5% solution, which indicates that the benefit of surfactants does not increase monotonically with concentration. Once the concentration exceeds the critical micelle concentration and the surface tension reaches its plateau, further additions provide little additional wetting and may increase viscosity or foam persistence in ways that do not aid penetration. This finding has direct economic significance because it supports low dosing rates in the range of 1–3%, which minimises the quantity of concentrate that must be transported to remote fire sites. The palm-based formulation of Subekti et al. (2019), dosed at 3.33 wt%,

achieved a more modest water saving of 9.89%, which may reflect differences in test configuration, foam expansion, and the absence of co-solvents and chelators that were present in the Japanese soap-based agent. Optimisation of palm-based formulas through mixture designs is therefore a logical next step (Subekti et al., 2024).

It should also be noted that the agent evaluated by Kanyama et al. (2023, 2025) was a commercial soap-based product developed from earlier work on eco-friendly soap foams for forest fires (Kawahara et al., 2016), and that the authors disclosed a commercial interest in its manufacture. Independent replication with locally produced palm-based agents would therefore strengthen the evidence base. Nevertheless, the consistency between the field data, the independent laboratory results of Santoso et al. (2021), and the palm-based results of Subekti et al. (2019) supports the general conclusion that fatty acid soap and surfactant agents substantially improve peat fire suppression efficiency.

Palm Oil-Derived Surfactant Candidates and Their Production Routes

Three classes of palm oil-derived surfactants emerge from the literature as candidates for peat fire foam concentrates: fatty acid soaps, methyl ester sulfonates, and nonionic sugar-based surfactants such as alkyl polyglucosides, which can be produced from palm-derived fatty alcohols. Their production routes, reported properties, advantages, and limitations are compared in Table 3.

Table 3. Candidate Palm Oil-Derived Surfactants for Peat Fire Foam Concentrates

No.	Surfactant Class	Production Route and Reported Conditions	Reported Properties, Advantages, and Limitations
1	Fatty acid soaps (sodium or potassium laurate, palmitate, oleate)	Saponification–neutralisation of palm fatty acids with NaOH or KOH; e.g., oleic acid with 30% alkali at a 1:1 molar ratio and 50 °C (Wahyuni & Dhora, 2019); simple two-reactor process of saponification and homogenisation (Rivai et al., 2017; Subekti et al., 2017)	Na-oleate at 50 °C: pH 8.17, surface tension 17.76 dyne/cm, foam stability 32.10% (Wahyuni & Dhora, 2019); readily biodegradable and low toxicity (Kawano et al., 2014); sensitive to strong acidity and water hardness
2	Methyl ester sulfonate (MES)	Esterification–transesterification of CPO or waste oil to methyl esters, followed by sulfonation with $Na_2S_2O_5$ and Al_2O_3 catalyst (Deli et al., 2025), $NaHSO_3$ with CaO under microwave heating (Qadariyah et al., 2024), or gaseous SO_3 in falling-film reactors at industrial scale	Yield 88.27% and pH 7.51 with 0.75% Al_2O_3 (Deli et al., 2025); surface tension 32.62 dyne/cm, yield 48.06% at 450 W and 20 min (Qadariyah et al., 2024); tolerant of acidic and hard water; higher process complexity
3	Alkyl polyglucosides and related glycosides	Glycosidation of fatty alcohols (derivable from palm kernel oil) with glucose	Widely used as hydrocarbon co-surfactants in fluorine-free foams; form worm-like micelles influenced by fuel solubility (Islam & Lattimer, 2024); synergy with other surfactants increases fuel resistance (Ateş et al., 2025)

Fatty acid soaps represent the simplest and most mature option. Their production requires only the neutralisation or saponification of palm fatty acids with alkali, followed by blending, which can be carried out in jacketed stirred reactors at moderate temperatures. Rivai et al. (2017) produced prototype foaming agents from palm oil fatty acids and identified foam stability as the main quality indicator, while Wahyuni and Dhora (2019) showed that the type of alkali and the reaction temperature strongly influence product quality, with sodium oleate produced at 50 °C exhibiting the best overall characteristics. The chain-length distribution of palm oil is advantageous: lauric acid from palm kernel oil yields soaps with high solubility and rapid foaming, whereas palmitic and oleic acids from palm oil and its fractions provide longer chains that increase foam stability and film elasticity. The sodium laurate–potassium palmitate combination optimised by Subekti et al. (2019) and the potassium laurate–oleate system of Kanyama et al. (2023) both exploit this complementarity. Potassium soaps are generally more soluble than sodium soaps and are preferred for liquid concentrates.

The principal weakness of soaps is their sensitivity to water chemistry. Under acidic conditions soaps are protonated to free fatty acids, and in hard water they precipitate as calcium and magnesium soaps (Kanyama et al., 2023). Kalimantan groundwater is typically soft, but peat porewater can be markedly acidic, which may reduce soap activity at the point of contact with the fuel. Two engineering strategies mitigate this risk. The first is to include a biodegradable chelating agent, such as methylglycine diacetic acid (MGDA), which was incorporated at 20.4 wt% in the field-tested concentrate, and to adjust the concentrate pH to a mildly alkaline value (Kanyama et al., 2023). The second is to blend soaps with surfactants that tolerate acidity and hardness, such as MES.

Methyl ester sulfonate offers precisely this tolerance. As a sulfonated anionic surfactant, MES remains ionised and soluble across a wide pH range and is less prone to precipitation with divalent ions. Indonesian research has demonstrated several synthesis routes suitable for different scales. At laboratory and small-industry scale, sulfonation of palm methyl esters with sodium metabisulfite in the presence of an Al_2O_3 catalyst achieved an MES yield of 88.27% (Deli et al., 2025), and microwave-assisted sulfonation of waste cooking oil methyl esters with $NaHSO_3$ and a CaO catalyst produced MES with a surface tension of 32.62 dyne/cm in only 20 minutes (Qadariyah et al., 2024). The use of waste cooking oil, of which Indonesia collected about 3 million kilolitres in 2019 according to the data cited by Qadariyah et al. (2024), further improves the circularity of the process, and similar routes have been applied to produce MES from used cooking oil for detergent formulations (Yusmin & Jumal, 2025). At industrial scale, continuous sulfonation with gaseous SO_3 in falling-film reactors is the established technology. The main trade-offs of MES relative to soaps are the greater complexity of the process, the need for careful control of sulfonation, neutralisation, and colour, and the higher capital cost.

Nonionic glycoside surfactants complete the toolkit. Alkyl polyglucosides are already used as co-surfactants in commercial fluorine-free foams because they are readily biodegradable, have low toxicity, and act synergistically with anionic and siloxane surfactants (Ateş et al., 2025; Islam & Lattimer, 2024). In a peat fire context, a small proportion of a glycoside co-surfactant can stabilise mixed micelles, reduce the sensitivity of soaps to acidity, and improve foam texture. More broadly, the shift towards bio-based and biosurfactant ingredients is supported by their renewable origin, biodegradability, and growing market acceptance as petroleum-free substitutes (Nagtode et al., 2023).

Proposed Formulation Design and Process Flow

Building on the preceding analysis, this study proposes an integrated process route for the production of a palm oil-derived foam concentrate for peat fires, shown in Figure 2. The route begins with feedstocks available in Kalimantan, such as crude palm oil, palm kernel oil, palm stearin, palm fatty acid distillate, and waste cooking oil. These are pre-treated by hydrolysis or fractionation to obtain fatty acids, or by esterification and transesterification to obtain fatty acid

methyl esters. The fatty acids are converted to potassium or sodium soaps through saponification, while the methyl esters are converted to MES through sulfonation, neutralisation, and bleaching. The two surfactant streams are then combined with co-surfactants and additives in a blending stage to produce the concentrate, which is subjected to quality control before packaging and field deployment.

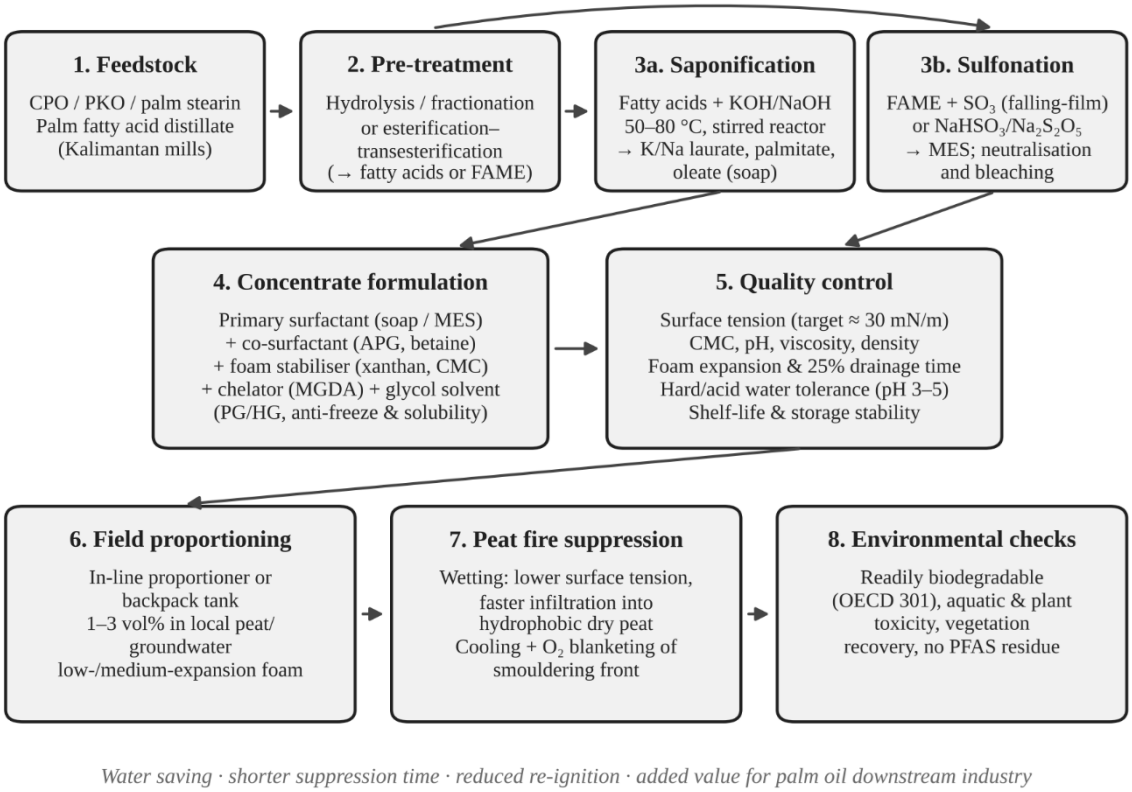


Figure 2. Proposed Process Flow for the Production and Application of a Palm Oil-Derived Foam Concentrate for Peatland Fire Suppression

The proposed formulation framework and evaluation matrix are presented in Table 4. The framework specifies indicative ranges for each component and target values for key quality parameters, together with the literature basis for each choice. The ranges are intended as starting points for laboratory optimisation using statistical mixture designs, such as the D-optimal approach already applied to palm-based foaming agents (Subekti et al., 2024), rather than as final specifications.

Table 4. Proposed Formulation Framework and Evaluation Matrix for a Palm Oil-Derived Peat Fire Foam Concentrate

No.	Component or Parameter	Proposed Range or Target	Basis in the Literature
1	Primary surfactant: potassium/sodium soaps of lauric, palmitic, and oleic acids	10–18 wt% of concentrate	15% sodium laurate with 3% potassium palmitate (Subekti et al., 2019); 4.3% lauric and 6.8% oleic acid as K-soaps (Kanyama et al., 2023)

No.	Component or Parameter	Proposed Range or Target	Basis in the Literature
2	Acid- and hardness-tolerant surfactant: palm-based MES	2–8 wt% of concentrate	Surface tension ≈32–33 dyne/cm and scalable synthesis (Deli et al., 2025; Qadariyah et al., 2024)
3	Nonionic co-surfactant: alkyl polyglucoside	1–5 wt% of concentrate	Synergistic foams and micellar stabilisation (Ateş et al., 2025; Islam & Lattimer, 2024)
4	Foam stabiliser: biopolymer such as xanthan gum or CMC, or mineral particles	0.1–0.5 wt% of concentrate	Particles and gels slow drainage and coarsening (Papagiannis et al., 2024; Zhao et al., 2024)
5	Chelating agent: MGDA	5–20 wt% of concentrate	20.4 wt% in field-tested concentrate (Kanyama et al., 2023)
6	Co-solvents: propylene glycol and hexylene glycol	10–20 wt% of concentrate	12.9% PG and 7.0% HG (Kanyama et al., 2023); low-carbon alcohols improve stability (Jia et al., 2024)
7	Application dose in water	1–3 vol%	1% superior to 5% (Santoso et al., 2021); 1 vol% in field trials (Kanyama et al., 2023, 2025); 3.33 wt% (Subekti et al., 2019)
8	Surface tension of 1% solution	≤ 32 mN/m	31.1–31.2 mN/m for effective agent versus 72.2 mN/m for water (Kanyama et al., 2023, 2025)
9	Peat penetration (water drop test)	≥ 5-fold faster than water	102 s versus 10 s; about six times faster (Kanyama et al., 2023, 2025)
10	Field efficacy	≥ 40% water saving; no re-ignition within 24 h	42–76% savings and no re-ignition (Kanyama et al., 2023, 2025)
11	Environmental safety	Readily biodegradable; no PFAS; vegetation recovery comparable to water	Kawano et al. (2014); Kanyama et al. (2023); Ying (2006)

The rationale for a hybrid soap–MES system deserves emphasis. Soaps provide low cost, rapid foaming, a proven field record on Kalimantan peat, and very favourable biodegradability, but they are vulnerable to acidity. MES compensates for this vulnerability while still deriving from the same palm feedstock. The nonionic glycoside acts as a bridge between the two anionic surfactants, reducing electrostatic repulsion in mixed micelles and improving foam texture. Biopolymer stabilisers such as xanthan gum increase the viscosity of the lamellae and retard drainage, while mineral or nanoparticle additives accumulate in Plateau borders and nodes, forming a protective layer at the gas–liquid interface that increases foam half-life (Papagiannis et al., 2024). In a gel-glycoside foam containing sodium silicate and sodium bicarbonate, the gelling and cross-linking agents shortened extinguishing time by 35.6%, and the 90% burnback time was about 45% longer than that of a conventional film-forming fluoroprotein foam (Zhao

et al., 2024), which points to further opportunities for peat applications in which a persistent, water-retaining blanket is desirable.

The co-solvents and chelator perform supporting functions that are often overlooked in laboratory studies but are critical for field deployment. Propylene glycol and hexylene glycol improve the solubility of soaps in concentrated form, lower the freezing point, and maintain a manageable viscosity for proportioning equipment (Kanyama et al., 2023). Low-carbon alcohols can also modulate foam structure; the addition of isobutanol to silicone–hydrocarbon systems has been shown to block foam liquid channels and increase foam stability (Jia et al., 2024). The chelator protects the soap fraction against divalent ions that may be present in mixed water sources, and its biodegradability should be verified alongside that of the surfactants.

From a process engineering perspective, the proposed route is modular and scalable. A small production unit for soap-based concentrate requires only two main vessels, one for saponification and one for homogenisation, which keeps investment costs low and allows production facilities to be located close to palm oil mills and fire-prone districts (Rivai et al., 2017; Subekti et al., 2017). An MES unit can be added later, initially using batch bisulfite or metabisulfite sulfonation and subsequently, if demand grows, continuous SO_3 sulfonation. The key unit operations, namely heat transfer during saponification, gas–liquid contacting during sulfonation, neutralisation with pH control, and high-shear blending, are standard in the Indonesian oleochemical industry.

Stoichiometry, Mass Balance, and Energy Requirements of Concentrate Production

To illustrate the chemical engineering basis of the proposed production route, an indicative mass balance was calculated for a 1,000 kg batch of soap-based concentrate, using the published composition of the field-tested agent (Kanyama et al., 2023) as a reference and assuming that the lauric and oleic acids are supplied from palm kernel and palm olein fatty acid fractions. The calculation uses molar masses of 200.32 g/mol for lauric acid, 282.46 g/mol for oleic acid, 56.11 g/mol for potassium hydroxide, and 18.02 g/mol for water. The results are summarised in Table 5.

Table 5. Indicative Mass and Energy Balance for a 1,000 kg Batch of Soap-Based Foam Concentrate

No.	Item	Calculated Value	Remarks
1	Lauric acid input	43.0 kg (0.215 kmol)	4.3 wt% of concentrate, after Kanyama et al. (2023)
2	Oleic acid input	68.0 kg (0.241 kmol)	6.8 wt% of concentrate, after Kanyama et al. (2023)
3	KOH for complete neutralisation	25.6 kg pure (53.2 kg of 48% solution)	1:1 molar ratio of KOH to fatty acid
4	KOH in reference formulation	22.1 kg pure (46.0 kg of 48% solution)	Corresponds to a degree of neutralisation of about 86%
5	Potassium soap formed	≈ 110.9 kg	Calculated from neutralised fatty acid plus K^+ replacing H^+
6	Residual free fatty acid	≈ 15.1 kg	Acts as foam booster; final pH adjusted after reaction
7	Water of neutralisation	≈ 7.1 kg	Incorporated into aqueous phase

No.	Item	Calculated Value	Remarks
8	Sensible heat to raise batch from 30 °C to 50 °C	≈ 70 MJ (≈ 19 kWh)	Assuming an average heat capacity of 3.5 kJ/(kg·K)
9	Heat released by neutralisation	≈ 20 MJ (order of magnitude)	Assuming about 50 kJ per mol of fatty acid neutralised

Several engineering insights emerge from this calculation. First, the alkali demand is modest: about 22–26 kg of pure KOH per tonne of concentrate. The reference formulation corresponds to a degree of neutralisation of approximately 86%, leaving a small fraction of free fatty acid. Partial neutralisation of this kind is a common technique in soap formulation, because free fatty acid can act as a foam booster and moderates the alkalinity of the product. The final pH of the reference concentrate was adjusted after saponification and reported as 10.73 (Kanyama et al., 2023). Second, the neutralisation reaction is exothermic and can supply a meaningful share of the heat required to bring the batch to the operating temperature of 50 °C, so that the external heating demand is low, on the order of tens of kilowatt-hours per tonne. Third, all the inputs other than the chelator are either palm-derived or common bulk chemicals, which supports the feasibility of local production.

For a hybrid formulation, part of the soap would be replaced by MES. The sulfonation step is more demanding than saponification. In small-scale processes based on bisulfite or metabisulfite, the reaction times reported range from 20 minutes under microwave heating (Qadariyah et al., 2024) to 5 hours with conventional heating and a heterogeneous Al_2O_3 catalyst (Deli et al., 2025), and the yield depends strongly on catalyst loading, molar ratio, and power input. These data suggest that an MES module should initially be designed as a separate batch unit supplying an intermediate to the blending stage, allowing the soap line to operate independently. Process optimisation of the MES module should target yield, residual unreacted methyl ester, and colour, since dark products may be less acceptable to users even if their surface activity is adequate.

Environmental Safety and the Transition Away from Fluorinated Foams

The environmental profile of the suppressant is particularly important in peatlands because the agent is applied directly to wetland soils that drain into canals, rivers, and fish habitats. The persistence of fluorinated surfactants in AFFF has been documented since the early 2000s (Moody & Field, 2000), and the resulting regulatory pressure has accelerated the development of fluorine-free alternatives (Ateia et al., 2023; Jahura et al., 2024). However, the F3 literature also shows that eliminating fluorine creates performance challenges for liquid fuel fires. Silicone–hydrocarbon fluorine-free foams cannot form an aqueous film on hydrocarbon surfaces and generally show better foam stability but poorer spreading than AFFF, with only certain formulations matching or exceeding AFFF performance (Sheng et al., 2020). Systematic analyses of foam databases have sought to correlate physical properties with suppression performance (Sudol et al., 2023), and studies of fuel–surfactant interactions show that fuel solubility alters micellar structure and foam degradation (Ateş et al., 2025; Islam & Lattimer, 2024).

These challenges are largely irrelevant to peat fires. Peat fires are Class A fires involving solid organic fuels, for which the critical functions are wetting, penetration, cooling, and water retention rather than film formation on liquid hydrocarbons. This distinction is crucial because it means that hydrocarbon and oleochemical surfactants that underperform in Class B qualification tests can be highly effective against peat fires. Research on Class A foams for wildfire suppression likewise focuses on foam stability and water retention rather than on fuel resistance (Papagiannis et al., 2024). For peatland applications, therefore, there is no technical

justification for using fluorinated foams, and palm-based soaps and surfactants represent a fit-for-purpose alternative.

Biodegradability and toxicity must nonetheless be demonstrated rather than assumed. Surfactants and their degradation products can affect aquatic organisms, and their fate in the environment depends on structure, concentration, and local conditions (Ying, 2006). Wildfire suppression chemicals in general may affect people and ecosystems, which calls for careful assessment before large-scale use (Kalabokidis, 2000). Studies of soap-based firefighting agents indicate lower toxicity than synthetic surfactant foams in model aquatic and semi-aquatic biotopes, with effects comparable to water spraying (Kawano et al., 2014), and field observations in Central Kalimantan showed vegetation recovery at soap-treated sites equivalent to that at water-treated sites after ten months (Kanyama et al., 2023). By contrast, ecotoxicity assays of commercial AFFF have shown toxic effects on crustaceans, plant germination and root growth, and earthworm avoidance behaviour (Rodrigues Junior et al., 2024). These comparisons support the environmental advantage of palm-based agents, but standardised testing, including ready biodegradability tests and aquatic toxicity tests with local species, should form an integral part of product development, as indicated in step 8 of Figure 2.

Comparison with Alternative Peat Fire Suppression Strategies

Surfactant foams should be evaluated against the other strategies available to fire managers in Kalimantan. The most common approach is surface spraying of water drawn from canals, wells, or tanks. Its main advantages are simplicity and familiarity, but its efficiency is limited by poor infiltration into dry peat, as discussed above, and by the large volumes required (Ramadhan et al., 2017; Santoso et al., 2021). A second approach is direct injection of water into the peat layer through lances or perforated pipes. Laboratory work indicates that injection can deliver water directly to subsurface smouldering zones (Mulyasih et al., 2022), and injection devices were used together with surface spraying in the GAMBUT field experiment (Hu et al., 2024). Injection is labour-intensive and slow to deploy over large areas, but it could be combined with surfactant solutions to improve lateral spreading of water within the peat.

A third group of strategies relies on rainfall or deliberate rewetting. Natural rainfall can suppress smouldering only when it is sufficiently intense and prolonged (Lin et al., 2020), and the contrasting emissions of the 2015 and 2023 El Niño seasons illustrate how strongly antecedent hydrology controls peat fire severity (Bruno et al., 2026). Rewetting through canal blocking is therefore the most important preventive measure, but it cannot extinguish an active fire quickly. A fourth strategy involves the use of additive solutions in water, including wetting agents, foams, and other water-based compositions. Experimental studies show that such compositions can suppress both flaming combustion and the thermal decomposition of model forest and peat fuels (Zhdanova et al., 2023), and that soap-based agents reduce water demand and re-ignition in the field (Kanyama et al., 2023, 2025).

Seen in this context, palm-based surfactant foams are not a substitute for rewetting and prevention, but a force multiplier for active suppression. They can be used with existing pumps, hoses, and backpack tanks, require no new heavy equipment, and increase the effectiveness of every litre of water delivered. Their greatest value lies in remote areas where water transport is the limiting factor and in deep, long-burning fires where water-only suppression is prone to failure and re-ignition. A combined strategy that integrates rewetting, early detection, surfactant-enhanced initial attack, and injection-based mop-up for persistent hot spots is likely to offer the best overall outcome.

Techno-Economic and Implementation Prospects in Kalimantan

The economic case for palm oil-derived foaming agents is supported by value-added analysis. Using the Hayami method, Subekti et al. (2020) calculated that producing peatland fire foaming agents from sodium laurate and potassium palmitate yields a value-added ratio of

80.87%, with the business being capital-intensive: labour accounted for 0.89% of the value added, other inputs for 3.73%, and entrepreneurial profit for 95.37%. Although these figures depend on market assumptions, they indicate that conversion of palm fatty acids into firefighting agents can be profitable and can create new jobs and economic activity in production areas. The water savings demonstrated in the field add a second economic dimension. Halving or more than halving the water demand reduces the number of pump runs, hose lengths, and personnel hours required per hectare, which is particularly valuable in remote peat domes where water must be drawn from canals or shallow wells.

The logistical implications can be quantified by scaling the field data to a per-hectare basis. Table 6 presents the water and concentrate requirements calculated from the spray densities reported by Kanyama et al. (2023, 2025), assuming a 1 vol% dose. The calculation shows that the use of a soap-based agent would save between about 34,000 and 165,000 litres of water per hectare of burning peat, depending on the depth and duration of the fire, while requiring only 360–740 litres of concentrate per hectare.

Table 6. Water and Concentrate Requirements per Hectare Calculated from Field Spray Densities

No.	Fire Scenario (Source)	Water Only vs. 1 vol% Agent (L/ha)	Water Saved and Concentrate Needed (L/ha)
1	Meso-scale plots (Kanyama et al., 2023)	81,000 vs. 47,000	34,000 saved; 470 concentrate
2	Large-scale natural peat (Kanyama et al., 2023)	72,000 vs. 36,000	36,000 saved; 360 concentrate
3	24 h fire, JR site (Kanyama et al., 2025)	160,000 vs. 38,000	122,000 saved; 380 concentrate
4	24 h fire, KL site (Kanyama et al., 2025)	239,000 vs. 74,000	165,000 saved; 740 concentrate

These figures highlight the leverage of the concentrate. Each litre of concentrate replaces roughly 70–320 litres of water that would otherwise need to be pumped, carried, or trucked to the fire. In remote peat domes, where water must often be drawn from shallow wells dug on site or carried by hand, such savings can determine whether a fire is contained during the initial attack or escapes to become a large, multi-week event. The results also indicate that the benefit is largest for deep, prolonged fires, which are precisely the fires that cause the greatest carbon emissions and haze.

Implementation also requires attention to logistics and capacity. At a dose of 1 vol%, one litre of concentrate yields 100 L of firefighting solution, so a 20 L jerrycan is sufficient for about 2,000 L of solution. Proportioning can be achieved with simple in-line proportioners attached to portable pumps or by premixing in backpack tanks, both of which were used successfully in the Palangkaraya trials (Kanyama et al., 2023). Training for community fire brigades and government fire crews should emphasise application rate, since suppression efficiency depends on the quantity applied per unit time (Kanyama et al., 2023; Santoso et al., 2021). Local production in Kalimantan would shorten supply chains and enable rapid stock replenishment during the dry season. Integration with prevention measures, including peat rewetting, early detection, and fire danger rating, remains essential, because suppression technology can reduce but not eliminate the impacts of large fire seasons (Bruno et al., 2026; Schmidt et al., 2024).

Quality Assurance and Laboratory Validation Protocol

Because the formulation framework is derived from published evidence, it must be validated experimentally before field deployment. A staged validation protocol is proposed. In

the first stage, candidate concentrates prepared according to Table 4 would be characterised for density, viscosity, pH, freezing point, and storage stability at elevated temperature, and their 1 vol% solutions would be characterised for surface tension, CMC, foam expansion ratio, and drainage time. Testing should be repeated in deionised water, in synthetic acidic water at pH 3–5, and in water collected from Kalimantan peat canals, to confirm performance under realistic water chemistry (Kanyama et al., 2023).

In the second stage, the penetration performance would be assessed using water drop penetration tests and column infiltration tests on dried peat collected from Central Kalimantan, comparing each formulation with water and with a reference soap agent (Kanyama et al., 2023, 2025). In the third stage, small-scale smouldering suppression experiments would be conducted in an instrumented reactor following the method of Santoso et al. (2021), recording suppression time, fluid demand per kilogram of peat, temperature histories at several depths, and re-ignition after a defined waiting period. The 50 °C extinction criterion adopted in previous studies would provide comparability (Kanyama et al., 2023; Santoso et al., 2021). In the fourth stage, mixture-design optimisation would refine the formulation (Subekti et al., 2024), and the best candidates would be evaluated for ready biodegradability and acute toxicity to aquatic and terrestrial organisms, with reference to the endpoints used in recent foam ecotoxicity studies (Kawano et al., 2014; Rodrigues Junior et al., 2024).

In the final stage, field trials on experimental plots in Central Kalimantan would compare palm-based agents with water at equal application rates, using thermal imaging to track hot spots and post-fire monitoring of vegetation, peat chemistry, and canal water quality (Kanyama et al., 2023). Emission measurements during suppression, following the approach of the GAMBUT experiment, would provide additional insight into whether surfactant-enhanced suppression reduces smoke production during the critical mop-up phase (Hu et al., 2024). The results of this protocol would allow the framework in Table 4 to be converted into a product specification suitable for procurement by disaster management agencies.

Research Gaps, Novelty, and Implications

The synthesis identifies several gaps that should guide future research. First, field evidence for soap-based agents on Kalimantan peat comes predominantly from a single research group using a commercial Japanese formulation, and independent field trials of locally produced palm-based agents are still limited. Second, the performance of MES-containing and hybrid formulations on peat fires has not yet been reported, even though MES synthesis from Indonesian feedstocks is well established. Third, the behaviour of surfactant agents in strongly acidic peat porewater and their interaction with peat organic matter, including adsorption losses, require systematic study. Fourth, long-term ecological monitoring beyond vegetation recovery, including effects on peat hydrology, microbial communities, and aquatic fauna in canals, is lacking. Fifth, the influence of surfactants on post-fire peat wettability and on the risk of subsequent re-ignition or accelerated drying should be investigated, since rewetted peat can behave differently from naturally moist peat.

The novelty of this study lies in bridging these strands into a single, chemically grounded framework. Previous work has addressed either the fire science of peat suppression or the synthesis of palm-based surfactants, but not both in an integrated process and product design. The proposed hybrid soap–MES–glycoside system, the explicit incorporation of acidic-water tolerance and chelation, the quantitative quality targets derived from field evidence, and the modular process route linking palm feedstocks to field application together constitute an original contribution. The framework is directly testable through laboratory mixture designs, small-scale smouldering experiments using the methods of Santoso et al. (2021), and field trials following the protocols of Kanyama et al. (2023, 2025).

The implications extend across science, industry, and policy. Scientifically, the study demonstrates how principles of interfacial science and chemical product design can be applied

to an environmental hazard dominated by smouldering combustion. Industrially, it identifies a new, high-value outlet for palm fatty acids, palm methyl esters, and waste cooking oil, consistent with national policies promoting palm oil downstreaming. For disaster management agencies, it provides evidence-based criteria for selecting and procuring PFAS-free suppressants that are effective on peat and safe for wetland ecosystems. Ultimately, a locally produced palm-based foam concentrate could help convert one of Kalimantan's major commodities into part of the solution to one of its most persistent environmental problems.

CONCLUSION

This study concludes that an environmentally friendly foam fire-extinguishing agent based on palm oil-derived plant-based surfactants is a scientifically sound and practically feasible solution for peatland fire suppression in Kalimantan. Peat fires are dominated by deep, persistent smouldering in a hydrophobic fuel matrix, so their suppression depends on how efficiently water infiltrates and remains in the burning zone rather than on the total volume applied. Surfactants address this limitation physically by lowering surface tension to about 30 mN/m, accelerating infiltration, improving cooling, forming water-retaining foam blankets, and reducing re-ignition. Field and laboratory evidence shows that fatty acid soap agents applied at about 1 vol% cut water demand by 42–76% and suppression time by about 60% relative to water alone, without impairing vegetation recovery. Palm oil provides all the necessary building blocks: fatty acid soaps for low-cost, rapid foaming; methyl ester sulfonate for tolerance to acidic and hard water; and glycoside co-surfactants for micellar synergy. On this basis, the study proposes a hybrid soap–MES–glycoside concentrate with biodegradable stabilisers, a chelator, and glycol co-solvents, dosed at 1–3 vol%, together with a modular production route and quantitative quality targets.

Several steps are recommended for future work. Laboratory optimisation of the proposed formulation should use statistical mixture designs and standard smouldering peat experiments. Independent field trials should then compare locally produced palm-based agents with water and commercial products on Kalimantan peat. Ready biodegradability and aquatic toxicity should be assessed with local species, and the long-term effects on peat hydrology and biota should be monitored. Techno-economic and life-cycle assessments of small-scale production units located near palm oil mills are also needed. Government agencies, the palm oil industry, and universities in Kalimantan are encouraged to collaborate on pilot production and on incorporating PFAS-free palm-based foams into peatland fire management protocols.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used Claude (Anthropic) in order to assist with literature searching, structuring the manuscript, drafting, and English-language editing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Methodology; Project administration; Writing - original draft; Writing - review and editing.
Author 2: Data curation; Formal analysis; Investigation; Visualization.
Author 3: Supervision; Validation; Writing - review and editing.

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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