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Limestone-Derived Fire Suppression Systems: A Sustainable Dual-Phase Framework for Materials Engineering

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Abstract: Fire suppression remains a critical concern for households, industries, and municipalities. Traditional agents such as halons, phosphate powders, and foams have been effective, but they pose risks related to toxicity, environmental damage, and cost (Babrauskas, 2003; UNEP, 2020). This paper introduces a conceptual framework for sustainable fire suppression technologies derived from limestone ($CaCO_3$), emphasizing their potential to provide eco-friendly and cost-effective alternatives to conventional extinguishers. The proposed approach highlights the conversion of limestone into calcium hydroxide (Ca $(OH)_2$) and carbon dioxide (CO_2), creating a dual suppression mechanism: thermal absorption, chemical neutralization, and oxygen displacement.

The study integrates a review of existing suppression methods, the thermodynamics of limestone transformations, and a proposed methodology for production and testing. The framework aligns fire safety with green chemistry and circular economy principles (Anastas & Warner, 2000), while case-based reflections demonstrate potential applications across cement plants, residential complexes, transportation, and electrical systems. Key strengths such as abundance, affordability, and sustainability are discussed alongside limitations, including storage challenges and CO_2 handling risks.

The findings suggest that limestone-derived suppressants could reshape material engineering by advancing sustainable mineral applications, optimizing particle properties for enhanced performance, and promoting industrial reuse of CO_2. While conceptual in nature, this work establishes the foundation for future research involving experimental validation, nanostructured formulations, hybrid systems, and real-world trials.

Keywords: *Fire Suppression, Calcium Hydroxide, Carbon Dioxide, Limestone, Sustainability, Material Engineering, Circular Economy.*

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I. INTRODUCTION

Fire has historically been both a tool for human development and a constant hazard. With rapid industrialization, urban expansion, and increasingly complex infrastructures, fire safety is now recognized as a global engineering and societal priority (Drysdale, 2011). Major fire incidents in industrial complexes, residential areas, fuel depots, and electrical installations not only result in loss of life but also cause severe environmental and economic damage. Effective fire suppression technologies are therefore critical for protecting human life, infrastructure, and ecological systems.

Conventional extinguishing technologies including halon-based systems, foams, carbon dioxide, and dry chemical powders have been widely deployed due to their proven effectiveness (Babrauskas, 2003). However, over the past three decades, researchers and policymakers have raised concerns about their environmental and health impacts. For example, halons were banned under the Montreal Protocol because of their ozone-depleting potential (UNEP, 2020), while phosphate- and bicarbonate-based powders are known to leave toxic and corrosive residues (Liu et al., 2020). These issues have led to a growing demand for sustainable, eco-friendly fire suppression systems.

In parallel, material engineering has played a key role in advancing fire safety by enabling the design of fire-resistant and fire-suppressing materials. This field provides tools to analyze thermal behavior, structural integrity, and reactivity under high-temperature conditions (Sharma & Prasad, 2019). Within this context, limestone ($CaCO_3$) and its derivatives quicklime (CaO) and calcium hydroxide (Ca $(OH)_2$) emerge as promising candidates for environmentally benign suppression technologies.

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- *Background*

Limestone is among the most abundant and widely distributed natural resources, traditionally used in construction, cement production, and environmental engineering (Boynton, 1980). When heated during calcination, $CaCO_3$ decomposes into CaO and CO_2; subsequent hydration of CaO produces Ca $(OH)_2$, a material with strong thermal and neutralizing properties. Both Ca $(OH)_2$ and CO_2 have established relevance in fire suppression contexts.

Calcium hydroxide acts as a heat sink, absorbing significant amounts of energy during thermal decomposition and chemically disrupting combustion processes. Its strong basicity also allows it to neutralize acidic byproducts of fires. Meanwhile, CO_2 is already widely used in extinguishers for electrical and liquid fuel fires because it displaces oxygen while leaving no residue (Kaczmarek, 2018).

This dual utility makes limestone an attractive raw material for fire suppression. Its abundance and low cost further enhance its potential for large-scale deployment, particularly in regions where fire safety infrastructure remains underfunded or underdeveloped.

- *Problem Statement*

Despite major advances in fire protection, conventional suppression systems present persistent challenges:

- *Environmental Concerns*

Halogenated compounds and certain synthetic powders are linked to ozone depletion, greenhouse gas emissions, and ecological harm (UNEP, 2020).

- *Health Risks*

Residues from widely used dry chemical agents may irritate the skin and respiratory system, raising occupational safety concerns (Sharma & Prasad, 2019).

- *Economic Limitations*

High production costs, complex disposal requirements, and limited accessibility in resource-constrained regions reduce the effectiveness of existing systems (Liu et al., 2020).

These limitations highlight the need for next-generation suppression systems that are safer, more affordable, and environmentally responsible, without compromising performance.

- *Objectives of the Study*

- *This Study Aims to:*

✓ Propose a conceptual pathway for developing fire suppression agents from limestone in both powder and gaseous forms.
✓ Analyze the thermochemical processes underlying the decomposition of $CaCO_3$ and the reactivity of Ca $(OH)_2$ in fire suppression applications.
✓ Compare potential advantages and limitations of limestone-derived agents with conventional extinguishers.
✓ Formulate a conceptual framework that integrates green chemistry, material engineering, and fire safety principles (Anastas & Warner, 2000).

- *Contribution and Novelty*

This research contributes to the field of fire safety engineering by introducing a novel dual-phase fire suppression framework derived from limestone-based materials. The proposed system integrates two complementary mechanisms: the thermal absorption capacity of Ca $(OH)_2$ in solid phase, which reduces flame temperature, and the oxygen displacement effect of CO_2 in gaseous phase, which limits combustion. Unlike conventional suppression agents such as halons, foams, and monoammonium phosphate powders that rely on a single-phase mechanism and often pose significant environmental or economic challenges, this approach provides a synergistic, eco-friendly alternative.

The novelty of this study lies in reframing limestone derivatives traditionally used in construction and industry as sustainable fire suppression agents within a circular economy framework. By proposing the integration of mineral-based thermal absorption with CO_2 reutilization, this research bridges a gap between materials science, fire suppression, and environmental sustainability. To the best of the author's knowledge, this is the first conceptual study that links fire suppression strategies with climate-conscious resource utilization, thereby providing both theoretical insight and a roadmap for future experimental validation, industrial design, and policy alignment.

II. LITERATURE REVIEW

- *Conventional Suppression Agents*

- *Water-Based Systems*

Water is the most accessible and widely used extinguishing medium. Its effectiveness is based on its high heat capacity and vaporization enthalpy, which absorb thermal energy and cool the combustion zone (Drysdale, 2011). However, water has limited applicability in electrical or chemical fires due to conductivity and the risk of violent reactions.

- *Halons and Chemical Substitutes*

Halon-based agents were once celebrated for their rapid flame knockdown ability. However, their ozone-depleting potential led to global restrictions under the Montreal Protocol (Babrauskas, 2003; UNEP, 2020). Post-ban substitutes have struggled to balance suppression efficiency with environmental safety.

- *Dry Chemical Powders*

Agents such as monoammonium phosphate and sodium bicarbonate are widely used in portable extinguishers. They function by disrupting combustion chain reactions and smothering flames. Nevertheless, their corrosive and toxic residues often damage equipment and present health risks (Liu et al., 2020).

- *Carbon Dioxide Systems*

CO_2 suppresses fires by reducing oxygen concentration and cooling the combustion environment. It is particularly effective for electrical and flammable liquid fires. Yet, CO_2 systems require high storage pressures, and excessive exposure poses asphyxiation hazards (Kaczmarek, 2018).

➢ *Firefighting Foams*

Foams form a physical barrier between fuel and oxygen, making them suitable for hydrocarbon and liquid fuel fires. Despite their effectiveness, fluorinated foams present long-term persistence and ecological contamination risks (Seow, 2013).

➢ *Emerging Trends in Fire Suppression*

- *Non-Halogenated Flame Retardants*

Material scientists are increasingly focusing on halogen-free systems. Compounds such as phosphorus-, nitrogen-, and mineral-based retardants offer safer alternatives, though they often face cost and performance trade-offs (Morgan & Wilkie, 2014).

- *Nanomaterials in Suppression*

Nanotechnology is being explored to enhance suppression performance. Nanoclays, metal oxides, and carbon-based nanomaterials improve dispersion, thermal stability, and surface reactivity in suppression systems (Qian, Guo, & Wang, 2019).

- *Bio-Based and Renewable Agents*

Biopolymer foams and natural extracts are under study as eco-friendly suppression agents. While promising, they remain at early development stages and face durability limitations (Chen, Xu, Li, & Liu, 2021).

Table 1 Comparison of Existing Fire Suppression Methods

Fire Suppression Agent	**Effectiveness**	**Environmental Impact**	**Cost**	**Limitation**
Halons	High	Ozone- depleting	High	Phased out due to environmental harm
Phosphate-based powder	Medium	Moderate	Medium	Leaves residue can damage equipment
Foam	Medium	Low to Moderate	Medium	Limited effectiveness of chemical fires
CO2	High	Low	High	Requires confined space, asphyxiation risk
Water Mist	Medium	Low	Medium	Ineffective on chemical and electrical fires
Proposed Ca (OH)2 + CO2 Dual- Phase System	High	Low	Medium	Addresses chemical and electrical fires efficiently

➢ *Relevance of Limestone-Derived Materials*

Calcium hydroxide, produced from limestone, offers dual suppression potential. Its decomposition absorbs heat and produces water vapor, while its alkalinity neutralizes acidic gases such as HCl and SO_2. Simultaneously, CO_2 released during calcination serves as an oxygen-displacing suppressant (Boynton, 1980).

This positions limestone as a raw material that can simultaneously address sustainability and performance requirements in fire safety. Unlike many synthetic suppressants, limestone-derived agents are abundant, inexpensive, and naturally degradable.

➢ *Gaps in the Literature*

- Limited exploration of limestone-based compounds as primary fire suppressants.
- Absence of integrated frameworks combining Ca $(OH)_2$ powders and CO_2 systems.
- Minimal research linking material engineering characterization (XRD, SEM, TGA) with fire suppressant performance.
- Lack of studies situating limestone fire suppressants within sustainability and circular economy contexts

This research addresses these gaps by proposing a conceptual framework for developing eco-friendly fire suppression agents from limestone, grounded in material engineering science.

➢ *Theoretical Foundation*

- *Fire Dynamics and Suppression Principles*

The basic chemistry of fire is captured in the "fire triangle," which requires fuel, oxygen, and heat to sustain combustion. Removing or interfering with any of these three elements disrupts the chain reaction and extinguishes the fire (Drysdale, 2011). Suppression agents generally function through one or more of the following mechanisms:

- ✓ Cooling: – lowering the temperature below ignition levels.
- ✓ Smothering: – displacing or isolating oxygen.
- ✓ Inhibition: – chemically interrupting flame-propagating free radicals.
- ✓ Neutralization: – reacting with or absorbing hazardous byproducts.

- *Material Properties of Calcium Hydroxide*

Calcium hydroxide (Ca $(OH)_2$), derived from hydration of quicklime, has properties that are advantageous for suppression. Its decomposition at high temperatures absorbs heat, reducing the energy available for combustion. Additionally, its strong alkalinity allows it to neutralize acidic species often generated in structural and industrial fires (Morgan & Wilkie, 2014; Sharma & Prasad, 2019).

Ca $(OH)_2$ also acts as a physical barrier when dispersed in powder form, covering surfaces and reducing heat transfer. This combination of thermal absorption, neutralization, and surface shielding provides multiple lines of defense in fire suppression.

- *Role of Carbon Dioxide*

Carbon dioxide, released during limestone calcination, is already a well-established fire suppressant. It extinguishes flames primarily by lowering oxygen concentration and through gas expansion cooling effects. Despite its strengths, CO_2 poses risks of asphyxiation in enclosed spaces, requiring careful engineering control in deployment (Kaczmarek, 2018).

- *Integrating a Dual-Phase Model*

When considered together, Ca $(OH)_2$ and CO_2 represent a dual-phase suppression strategy:

- ✓ Solid-phase action (Ca $(OH)_2$): heat absorption, surface shielding, and neutralization.
- ✓ Gas-phase action (CO_2): oxygen displacement and flame smothering.

This integrated framework combines the benefits of both powder- and gas-based systems while using a material that is low-cost, abundant, and environmentally benign (Boynton, 1980).

III. METHODOLOGY

This study adopts a conceptual and literature-based approach rather than direct experimental testing. The methodology was designed to establish a scientific foundation for limestone-derived fire suppression systems and to frame their relevance within sustainability and material engineering.

➢ *Literature Review*

A comprehensive survey of academic research, industry reports, and regulatory guidelines was conducted to assess conventional suppression technologies. Key challenges such as environmental impact, occupational health risks, and material limitations were identified (Babrauskas, 2003; Liu et al., 2020; Seow, 2013). This stage provided the baseline against which limestone-derived approaches were evaluated.

➢ *Thermochemical Analysis*

The thermodynamic properties of limestone and its derivatives were examined using published data on decomposition and hydration reactions. Special focus was placed on:

- The endothermic decomposition of $CaCO_3$ into CaO and CO_2.
- The hydration of CaO into Ca $(OH)_2$.
- The subsequent decomposition of Ca $(OH)_2$, which absorbs heat and releases H_2O vapor (Boynton, 1980; Sharma & Prasad, 2019).

These reactions were analyzed for their fire suppression potential in terms of cooling, oxygen displacement, and neutralization of byproducts.

➢ *Conceptual Framework Development*

Findings from the literature and thermochemical analysis were synthesized into a dual-action conceptual model. The model emphasizes Ca $(OH)_2$ as a solid-phase suppressant providing thermal absorption and neutralization, and CO_2 as a gas-phase suppressant responsible for oxygen displacement (Kaczmarek, 2018).

➢ *Sustainability and Circular Economy Integration*

The proposed framework was evaluated against principles of green chemistry (Anastas & Warner, 2000) and circular economy models. Key opportunities identified include:

- Repurposing CO_2 emissions from industrial calcination as fire suppressants.
- Reducing reliance on toxic halogenated or fluorinated agents (UNEP, 2020).
- Enhancing global accessibility by leveraging an abundant and inexpensive raw material.

➢ *Application Scenarios*

To demonstrate practical feasibility, case-based reflections were conducted in four contexts:

- Cement manufacturing plants, where calcination CO_2 emissions could be redirected for suppression.
- Residential settings, where non-toxic residues are essential for occupant safety.
- Electrical installations, where non-conductive, residue-free suppression is required.
- Transportation systems, where lightweight and eco-friendly suppression agents are critical (Chen, Xu, Li, & Liu, 2021).

These reflections help illustrate both the promise and limitations of limestone-derived suppressants in real-world contexts.

➢ *Conceptual Framework*

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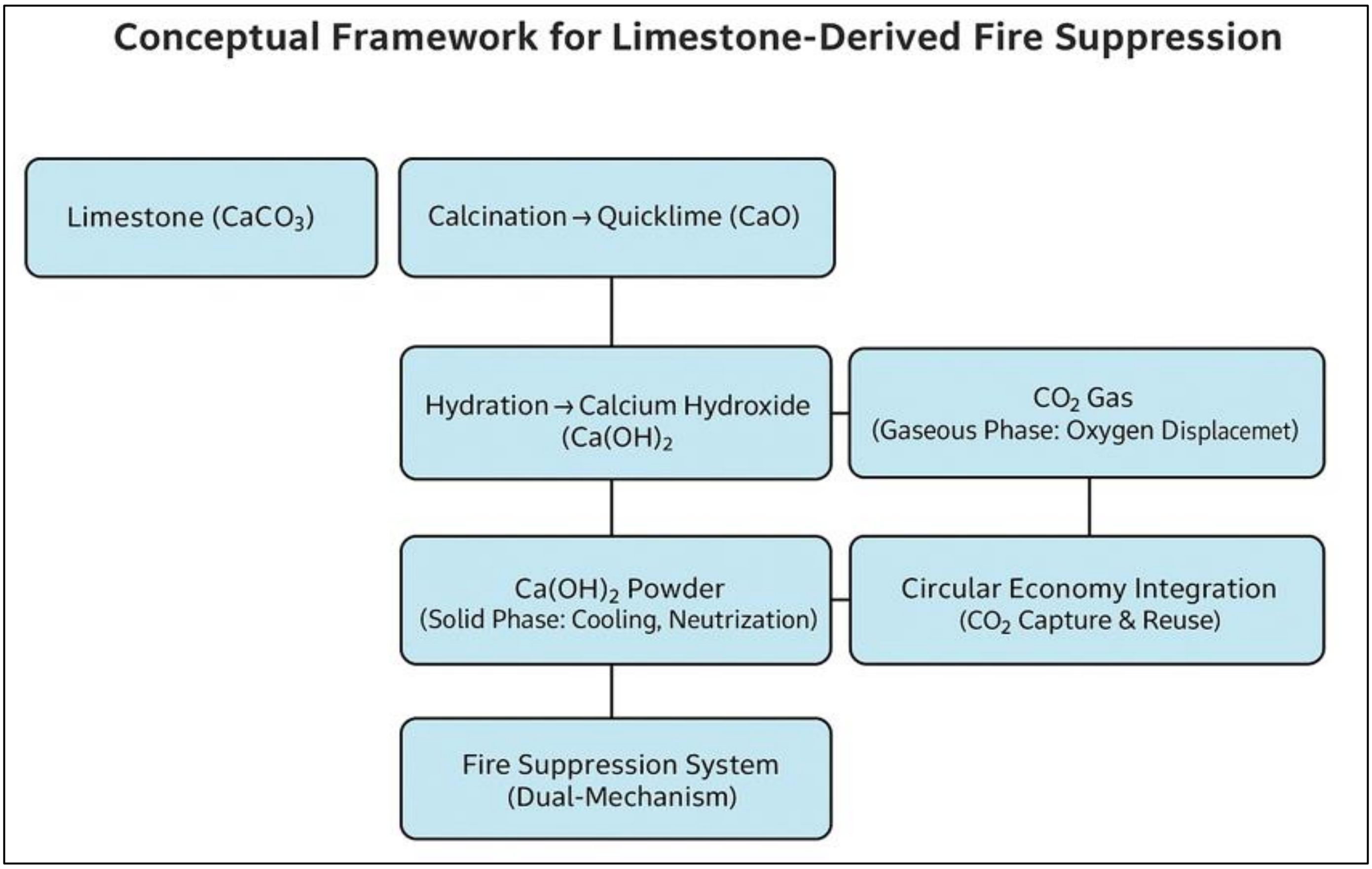

Fig 1 Conceptual Framework

The proposed framework positions limestone-derived compounds as sustainable fire suppression agents. It is structured around four interrelated dimensions:

- *Material Transformation Pathway*

Limestone ($CaCO_3$) undergoes a sequence of transformations that yield both solid- and gas-phase suppressants:

- ✓ Calcination: $CaCO_3 \rightarrow CaO + CO_2$
- ✓ Hydration: $CaO + H_2O \rightarrow Ca(OH)_2$
- ✓ Thermal decomposition: $Ca(OH)_2 \rightarrow CaO + H_2O$ vapor

This sequence enables a single raw material to produce agents with dual suppression functions: Ca $(OH)_2$ powder and CO_2 gas (Boynton, 1980).

- *Dual-Action Suppression Mechanism*

- ✓ Solid-phase action (Ca $(OH)_2$): Absorbs heat during decomposition, neutralizes acidic gases such as HCl and SO_2, and forms a surface layer that limits heat transfer (Sharma & Prasad, 2019).
- ✓ Gas-phase action (CO_2 and H_2O vapor): Displaces oxygen, dilutes flammable gases, and suppresses flames without leaving harmful residues (Kaczmarek, 2018).

The synergy of these mechanisms provides a multi-layered suppression effect that may outperform single-mode extinguishers.

- *Sustainability Integration*

The framework embeds sustainability principles throughout its design:

- ✓ Resource efficiency: Limestone is abundant, globally distributed, and inexpensive.
- ✓ Circular economy alignment: CO_2 produced in industrial calcination can be captured and reused in suppression systems, reducing greenhouse gas emissions (Anastas & Warner, 2000; UNEP, 2020).
- ✓ Reduced environmental footprint: Unlike halogenated foams or powders, residues of $Ca(OH)_2$ are non-toxic and biodegradable (Morgan & Wilkie, 2014).

- *System-Level Considerations*

Successful deployment requires addressing engineering and safety factors:

- ✓ Particle design: Size, porosity, and surface area influence the reactivity and cooling capacity of Ca $(OH)_2$ (Qian, Guo, & Wang, 2019).
- ✓ Storage stability: The hygroscopic nature of Ca $(OH)_2$ demands sealed packaging or stabilizing additives.
- ✓ Delivery systems: Limestone-derived agents could be integrated into portable extinguishers, sprinkler systems, or fixed industrial units (Chen, Xu, Li, & Liu, 2021).

➢ *Conceptual Model (Narrative Summary)*

The framework can be visualized as a three-layer system:

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- Inputs: - Raw limestone, hydration water, and captured industrial CO_2.
- Transformations: - Calcination, hydration, and decomposition reactions producing Ca $(OH)_2$ and CO_2.
- Outputs: - Fire suppression via cooling, oxygen displacement, and neutralization, with minimal environmental impact.

➤ *Implications for Material Engineering Science*

The conceptualization of limestone-derived fire suppression agents holds several important implications for the discipline of material engineering.

- *Advancing Sustainable Applications of Common Minerals*

This research reframes limestone, traditionally viewed as a construction and cement precursor, into a functional fire suppression material. By doing so, it expands the scope of sustainable applications for abundant minerals and demonstrates how conventional raw materials can be repositioned in line with modern environmental challenges (Boynton, 1980).

- *Alignment with Green Chemistry Principles*

The approach is consistent with the 12 principles of green chemistry proposed by Anastas and Warner (2000). Specifically, it minimizes toxicity, reuses byproducts, and leverages renewable or naturally abundant resources. By substituting hazardous halogenated compounds with Ca $(OH)_2$ and recycled CO_2, the framework demonstrates a low-impact strategy that is both chemically and ecologically sound.

- *Contribution to Circular Economy Strategies*

One of the strongest implications lies in the integration of circular economy principles. CO_2 emissions, a byproduct of calcination in cement and lime industries, can be recaptured and applied in fire suppression rather than being vented into the atmosphere. This dual-purpose use of industrial byproducts transforms waste streams into valuable safety resources (UNEP, 2020).

- *Optimization of Material Properties*

The framework invites further investigation into the material properties of $Ca(OH)_2$. For example, adjusting particle morphology, surface chemistry, and porosity could improve suppression efficiency. Nanostructured or surface-modified $Ca(OH)_2$ may provide enhanced thermal absorption, faster reactivity, and longer shelf life (Qian, Guo, & Wang, 2019). These directions highlight opportunities for innovation within materials science and nanoengineering.

- *Industrial and Societal Relevance*

Given its abundance and affordability, limestone-derived fire suppression systems could improve access to safety technologies in regions where conventional extinguishers are economically prohibitive. This democratization of fire safety aligns with global sustainability and equity goals, making the research particularly relevant to developing economies (Chen, Xu, Li, & Liu, 2021).

IV. CASE REFLECTIONS

The adaptability of limestone-derived fire suppression systems can be illustrated through several potential application scenarios. These reflections demonstrate how the framework could be applied in diverse sectors while also revealing practical considerations for implementation.

➤ *Industrial Case: Cement Manufacturing*

Cement factories are a major source of CO_2 due to limestone calcination. Redirecting a portion of this CO_2 into fire suppression systems could reduce the industry's carbon footprint while enhancing safety. At the same time, $Ca(OH)_2$ produced in situ could be packaged into extinguishers for onsite use, creating a closed-loop model that merges waste mitigation with safety infrastructure (UNEP, 2020).

➤ *Electrical Installations*

Facilities such as data centers and industrial electrical rooms require extinguishing systems that are non-conductive and leave minimal residue. CO_2 derived from limestone processes offers a viable alternative to synthetic halons, which are both hazardous and environmentally damaging. While the asphyxiation risk of CO_2 must be managed through ventilation and monitoring, its circular economy origin provides an added sustainability advantage (Kaczmarek, 2018).

➤ *Residential and Commercial Buildings*

For household and commercial fire protection, portable extinguishers could be designed to combine both $Ca(OH)_2$ powders and CO_2 cartridges. Such multi-class extinguishers could be particularly effective in environments like kitchens, where flames may need oxygen displacement while smoke neutralization prevents toxic exposure. This dual-action system could provide residents with safer and eco-friendlier alternatives to conventional dry powders or foams (Chen, Xu, Li, & Liu, 2021).

➤ *Transportation Systems*

In vehicles, ships, and aircraft, fire suppression equipment must be lightweight, non-corrosive, and safe in confined spaces. Limestone-derived agents could meet these needs by delivering effective suppression while avoiding the corrosive residues of conventional powders or the persistence of fluorinated foams (Seow, 2013). Combined CO_2 and $Ca(OH)_2$ systems may also reduce maintenance costs in transport fleets.

➤ *Summary*

These case reflections indicate that limestone-based fire suppressants are not limited to a single context but can be adapted across multiple sectors. However, they also highlight practical challenges such as powder storage, safe CO_2 containment, and integration into existing safety standards.

V. DISCUSSION

The proposed framework for limestone-derived fire suppression systems offers a basis for comparison with

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existing technologies. This section analyzes its relative advantages, limitations, and potential for commercialization.

➢ *Comparative Analysis with Conventional Agents*

- *Halons:*

Halon systems were once valued for their ability to interrupt combustion chemistry, but they were banned under the Montreal Protocol due to their severe ozone-depleting effects. In contrast, limestone-derived suppressants are non-toxic and environmentally benign (UNEP, 2020).

- *Dry Chemical Powders:*

Sodium bicarbonate, potassium bicarbonate, and ammonium phosphate are effective suppressants but tend to be corrosive and leave residues that can damage sensitive equipment. Ca $(OH)_2$ avoids many of these issues, though its hygroscopicity poses storage challenges (Liu, Zhang, & Sun, 2020).

- *CO_2 Systems:*

Conventional CO_2 extinguishers are widely used, but the CO_2 they release is typically sourced from energy-intensive processes. Limestone-derived CO_2 provides the same suppression function while contributing to a circular economy approach, turning industrial emissions into a useful resource (Kaczmarek, 2018).

- *Foam Agents:*

Foam systems are effective against liquid fires, but fluorinated foams persist in the environment and have raised long-term ecological concerns. Limestone-based systems, by contrast, are biodegradable and free of persistent contaminants (Seow, 2013).

➢ *Strengths of the Framework*

- Raw material abundance: Limestone is inexpensive and globally available (Boynton, 1980).
- Environmental compatibility: Non-toxic, biodegradable, and aligned with climate sustainability goals (Anastas & Warner, 2000).
- Dual-functionality: Combines cooling, chemical neutralization, and oxygen displacement.
- Versatility: Potentially applicable to Classes A, B, C, and D fires.

➢ *Challenges and Limitations*

- Moisture sensitivity: Ca $(OH)_2$ must be stored in airtight containers to prevent degradation.
- Powder handling: Fine particulates may present inhalation risks during discharge.
- CO_2 safety: Risk of asphyxiation in enclosed environments requires strict controls (Kaczmarek, 2018).
- Industrial adoption: Large-scale implementation depends on integration with cement and lime industries, which may require infrastructure modifications.

➢ *Commercialization Potential*

The transition from conceptual framework to real-world application depends on collaboration between industry and policy stakeholders. Possible pathways include:

- Industry partnerships: Cement manufacturers and fire safety companies could co-develop systems that utilize CO_2 and $Ca(OH)_2$ byproducts.
- Policy support: Carbon credit schemes and environmental regulations could incentivize industries to divert CO_2 emissions into suppression technologies (UNEP, 2020).
- Pilot testing: Small-scale industrial trials could validate technical feasibility and economic competitiveness compared with conventional agents.

VI. CONCLUSION

This study presented a conceptual framework for developing limestone-derived fire suppression systems as sustainable alternatives to conventional extinguishing agents. The approach relies on the dual use of calcium hydroxide (Ca $(OH)_2$) and carbon dioxide (CO_2), both derived from limestone transformations, to provide complementary suppression mechanisms.

From a materials engineering perspective, the research demonstrated that limestone's abundance, affordability, and chemical versatility make it an attractive raw material for fire safety applications. Ca $(OH)_2$ contributes to suppression by absorbing heat, releasing water vapor, and neutralizing acidic combustion products, while CO_2 displaces oxygen to extinguish flames. Together, these functions align with the fire triangle model, targeting both heat and oxygen to interrupt combustion (Drysdale, 2011).

The framework further emphasizes sustainability by aligning with green chemistry principles (Anastas & Warner, 2000) and supporting circular economy integration. Industrial CO_2 emissions from cement and lime production could be redirected toward fire suppression rather than released into the atmosphere, thus converting a climate liability into a safety resource (UNEP, 2020).

Case reflections illustrated how the concept could be adapted for industrial facilities, electrical installations, residential buildings, and transportation systems, showing broad relevance across sectors. However, the framework also faces challenges, including the hygroscopic nature of Ca $(OH)_2$, potential health risks from powder inhalation, and safety concerns related to CO_2 use in confined spaces (Kaczmarek, 2018).

Overall, this research suggests that limestone-based fire suppression systems represent a transformative opportunity for sustainable fire safety engineering. With further experimental validation, material optimization, and pilot-scale implementation, these systems could reduce reliance on toxic, costly, and environmentally damaging conventional extinguishers while contributing to global sustainability and climate goals.

FUTURE RESEARCH DIRECTIONS

While the conceptual framework demonstrates strong potential, further research is necessary to validate and optimize limestone-derived fire suppression systems. Future investigations should focus on three main areas:

➤ *Experimental Validation*

Controlled laboratory studies are needed to quantify the suppression performance of $Ca(OH)_2$ and CO_2 across different fire classes. Tests should evaluate:

- Extinguishing efficiency against solid, liquid, gas, and electrical fires.
- Reaction kinetics of $Ca(OH)_2$ decomposition at fire-relevant temperatures.
- Residue analysis, focusing on toxicity, cleanup, and material compatibility.

Such empirical work would provide the scientific evidence necessary to confirm the conceptual claims made in this study (Drysdale, 2011).

➤ *Material Optimization*

Further research in materials science should explore methods for enhancing the stability and effectiveness of $Ca(OH)_2$. Promising approaches include:

- Particle engineering: modifying size, porosity, and morphology to improve surface reactivity and storage stability (Qian, Guo, & Wang, 2019).
- Composite formulations: combining $Ca(OH)_2$ with nanomaterials or other minerals to enhance suppression efficiency.
- Encapsulation techniques: protecting $Ca(OH)_2$ from premature hydration and degradation in storage environments.

These studies would advance the engineering science dimension of the framework by creating next-generation suppressants.

➤ *Industrial and Policy Integration*

On a broader scale, future work should assess how limestone-derived systems can be integrated into industrial processes and safety regulations. Key considerations include:

- Life cycle assessment (LCA) to evaluate environmental benefits compared with traditional agents (Anastas & Warner, 2000).
- Economic analysis of cost competitiveness and scalability for mass production.
- Policy incentives, such as carbon credit schemes, to encourage industries to repurpose calcination CO_2 for fire suppression (UNEP, 2020).

These directions will determine the practical feasibility and societal impact of commercial deployment.

➤ *Summary*

By combining laboratory testing, materials innovation, and industry-policy collaboration, future research can transform the limestone-derived framework from a conceptual model into a validated, market-ready fire suppression technology.

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