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Development of Smart Fire Extinguishing Agents

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Abstract

The invention of smart fire extinguishing agents, which satisfy the growing need for efficient, eco-friendly, and adaptable fire suppression systems, is a significant advancement in fire safety. Traditional fire extinguisher chemicals, such as water, foam, and chemical powders, are effective, but they often have disadvantages, including toxicity, negative environmental effects, and inefficiency in difficult situations. Conversely, smart extinguishing agents maximize fire suppression through intelligent, tailored responses by utilizing advancements in material science, nanotechnology, and autonomous control systems. These agents employ intelligent components like phase-change materials, nanofluids, and stimuli-responsive polymers to adapt dynamically to fire conditions. For example, agents based on nanofluids enhance thermal conductivity, enabling more efficient suppression and faster heat absorption. Similarly, stimuli-responsive polymers modify their chemical characteristics in response to heat or flame, improving extinguishing effectiveness, whereas phase-change materials store and release energy to counteract abrupt temperature increases. The performance of these agents is further improved with the addition of intelligent systems, such as sensors and machine learning algorithms. Fire conditions are continuously monitored by embedded sensors, which enable accurate deployment according to variables, including fire kind, intensity, and spread dynamics. Proactive and effective response tactics are made possible by machine learning models that use real-time data analysis to forecast fire behavior. These devices solve significant flaws in traditional fire suppression methods by reducing collateral harm and resource waste. Sustainability is a key consideration in the development of smart fire extinguishing agents. To lessen the environmental impact of fire suppression operations, researchers are investigating environmentally friendly formulations, such as halogen-free chemicals, green aerosols, and biodegradable foams. Additionally, these agents are being developed for a variety of uses, ranging from home and commercial fires to more specific situations like electrical fires, wildfires, and fires in high-risk or confined spaces. There are still issues with long-term dependability, scalability, and cost-effectiveness. Ongoing multidisciplinary research, however, is quickly getting past these obstacles. Material scientists, engineers, and legislators are working together to develop smart fire safety solutions that have the potential to revolutionize communities, ecosystems, and industries. The technical advancements that supported the creation of smart fire extinguishing chemicals, their working principles, and their possible influence on contemporary fire safety are highlighted in this study. These agents provide a promising route toward more responsible and efficient fire suppression solutions by addressing environmental issues and improving flexibility, opening the door to safer and more sustainable surroundings.

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INTRODUCTION

Fire safety is a major concern in both home and commercial settings, which motivates ongoing advancements in firefighting technology. Water, foam, and dry chemicals are examples of conventional fire suppression solutions that have limits in terms of effectiveness, environmental impact, and adaptability to various fire conditions [1]. The creation of intelligent fire extinguishing agents has become a game-changing solution to these problems. Smart fire extinguishing agents offer targeted, effective, and eco-friendly fire suppression solutions by utilizing developments in material science, sensors, and control systems (Figure 1) [2].

Figure 1. Nanomaterials for fire extinguishing agents and extinguishing mechanisms.

These agents can dynamically adjust to various surroundings, operational situations, and fire classifications (A, B, C, D, or K). These could include, for example, self-propagating chemical processes, nanoparticles, or clever delivery systems that can increase fire suppression effectiveness and speed while reducing collateral damage [3]. Here, we highlight the benefits of smart fire extinguishing chemicals over conventional techniques while talking about their development, principles, and possible uses. The emphasis is on incorporating cutting-edge technology that redefines the capabilities of contemporary firefighting systems, such as smart sensors, artificial intelligence (AI), and environmentally friendly materials [4]. Society may drastically lower fire-related losses, save ecosystems, and guarantee safer living and working conditions by developing smart fire extinguishing agents.

THE KEY COMPONENTS AND STRATEGIES IN THE DEVELOPMENT OF SMART FIRE EXTINGUISHING AGENTS

(i) Self-activating fire extinguishing agents, (ii) intelligent delivery systems, (iii) chemical innovations, (iv) dynamic fire suppression, (v) multifunctional agents, and (vi) hybrid systems are the main elements and approaches used in the creation of smart fire extinguishing agents. Figure 2 shows a graphic representation of this.

Figure 2. The key components and strategies in the development of smart fire extinguishing agents.

Self-Activating Fire Extinguishing Agents

- *Thermal-Activated Agents:* Chemicals that, when exposed to high temperatures, emit extinguishing chemicals, are known as thermal-activated agents.

Figure 3. The different types of self-activating fire extinguishing agents.

Thermal-activated fire extinguishing agents are innovative materials designed to enhance fire suppression effectiveness through temperature-responsive mechanisms (Figure 3). These agents function by undergoing a phase change or chemical reaction when exposed to elevated temperatures, thereby, releasing active components that can suppress flames. The development of such agents addresses the need for more efficient fire control methods in various applications, including industrial settings, transportation, and residential environments.

The capacity of thermally activated compounds to react independently to fire conditions is one of their main benefits. This characteristic allows for rapid intervention, potentially reducing damage and improving safety. Common thermal-activated agents include phase-change materials (PCMs), which absorb heat and change from solid to liquid, thereby, facilitating heat management and flame suppression. Additionally, some agents release gases that displace oxygen or inhibit combustion reactions, further enhancing their effectiveness. Research into these materials has revealed a range of formulations, including composites that incorporate inorganic salts, polymers, and nanoparticles. The choice of components significantly influences the thermal stability, activation temperature, and extinguishing efficiency. Furthermore, advancements in nanotechnology have enabled the creation of agents with enhanced surface area and reactivity, leading to quicker activation and improved suppression capabilities.

- *Aerosol Fire Suppressants:* These are incredibly potent fine-particle aerosols that quickly stop combustion processes.

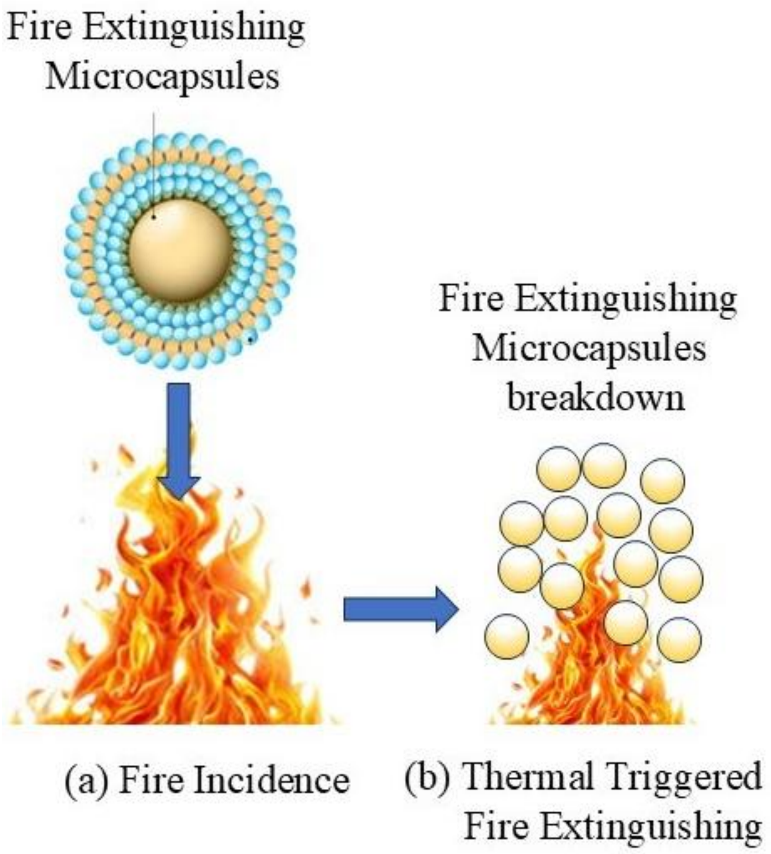

Figure 4. Microcapsules as effective fire extinguishing agents.

Microencapsulation is a cutting-edge technique that involves enclosing active substances within a protective coating, allowing for controlled release and enhanced effectiveness in various applications, including fire extinguishing agents (Figure 4). This innovative approach has gained attention in fire safety due to its ability to improve the stability, performance, and delivery of fire suppressants. Microencapsulated fire extinguishing agents can release their active components in response to specific thermal triggers, providing a targeted and efficient response to flames.

The process of microencapsulation involves creating tiny capsules, often in the range of micrometers, that can contain a variety of fire suppressants, including halocarbons, water-based solutions, or solid particles. These capsules can be engineered to break down at predetermined temperatures, releasing their contents precisely when needed. This mechanism not only enhances the effectiveness of the extinguishing agents but also minimizes environmental impact by reducing the release of chemicals into the atmosphere.

One of the primary benefits of microencapsulation is the ability to tailor the properties of the fire extinguishing agents, such as their activation temperature, release rate, and compatibility with various substrates. This customization allows for the development of multifunctional fire suppression systems that can be integrated into materials used in construction, textiles, and coatings, providing passive fire protection.

In another report, a temperature-sensitive intelligent gel (TSIG) was reported to be synthesized using methylcellulose (MC), polyethylene glycol (PEG), and sodium chloride (NaCl). The flow behavior of the TSIG under various conditions was examined through viscosity testing. Additionally, an infrared spectrometer was employed to investigate the microscopic flame-retardant mechanism of the TSIG. A large-scale fire-extinguishing simulation test bench was constructed at a coal mine site to evaluate the effect of TSIG on the coal oxidation reaction at different injection temperatures. The findings revealed that TSIG undergoes a liquid–solid phase transition when the temperature exceeds 60°C. When the ratio of MC: PEG: NaCl is 1:6:5, the TSIG exhibits optimal flow properties. Large-scale simulation experiments demonstrated that the injection of TSIG at coal temperatures between 300°C and 900°C significantly reduced CO concentrations, indicating excellent fire-extinguishing performance. The TSIG was found to inhibit the formation of free radicals during coal oxidation, disrupt the chain reaction responsible for spontaneous combustion, and effectively suppress the entire combustion process [5].

To address the spontaneous coal combustion (SCC), a novel irreversibly thermo-sensitive composite gel based on konjac glucomannan (KGM) and expandable graphite (EG) was meticulously developed for preventing SCC disasters and coal fires [6]. The composite gel's primary properties, including gelation time, water retention rate, rheological behavior, microstructure characteristics, and thermal decomposition properties, were systematically investigated. The findings revealed that the composite gel exhibits non-Newtonian fluid behavior with excellent self-repairing capability. It demonstrated controllable gelation properties, strong water retention, and favorable seepage capacity. Scanning electron microscopy (SEM) observations and thermogravimetric analysis (TGA) showed that the interspersed network structures of KGM embedded with EG exhibited higher density, greater physical strength, superior structural stability, and enhanced thermal stability. EG was closely adhered to the KGM hydrogel network, though distributed unevenly. High-temperature pyrolysis tests revealed that the decomposition rate of the composite gel increased to 0.234%/°C and 0.225%/°C at 266.5°C and 275.1°C, respectively. Low-temperature oxidation and fire-extinguishing experiments further demonstrated the composite gel's strong inhibition effects. The KGM@EG gel effectively reduced the high-temperature pyrolysis rate of coal, suppressed heat accumulation, minimized oxygen consumption, and decreased CO production during coal oxidation and combustion processes. These effects significantly lowered the likelihood of SCC and coal fires. Thus, the KGM@EG composite gel provides an efficient solution for preventing SCC and extinguishing coal fires, enhancing safety in coal mine operations. Additionally, the underlying mechanism of the thermo-sensitive gel's SCC-preventing and fire-extinguishing functions was revealed and proposed, offering valuable insights for future applications.

Coal mine fires pose significant threats to the safety of underground workers and cause substantial economic losses. When a fire occurs, the rapid rise in underground temperatures creates a critical hazard that must be controlled to prevent further disasters. So, a novel fire-extinguishing gel with high water absorption and resistance was developed using sodium carboxymethyl cellulose as the matrix [7]. Graft copolymerization of acrylic acid and 2-acrylamide-2-methylpropanesulfonic acid was used to create the gel, which produced a substance with exceptional fire resistance. The gel is very good at preventing and suppressing fires because of its exceptional water absorption ratio. Infrared spectroscopy, thermogravimetry, X-ray diffraction, and SEM were used to examine its microscopic processes and structural features. Property testing revealed that the gel exhibits a rapid water absorption rate, strong salt tolerance, and excellent water retention. Furthermore, it provides effective sealing and filling, significantly enhancing its fire-extinguishing performance.

Fires on heavy vehicles and trucks remain a significant threat to both the environment and human safety, often leading to severe consequences and injuries. By putting in place an efficient fire monitoring and extinguishing system, it is crucial to reduce the likelihood of a fire starting quickly and to provide drivers and residents enough time to safely evacuate. Existing fire extinguishing systems, however, have several drawbacks, such as limited compatibility with heavy vehicle types, insufficient system parameter monitoring, and the toxicity of the extinguishing agents employed in the environment. A unique integrated fire monitoring and suppression system for trucks and other large vehicles has been created in response to these difficulties. This innovative solution is designed to function effectively in any environment – both confined and open – by establishing a seamless connection between onboard diagnostic sensors and a plug-and-play fire extinguishing system. The system employs an environmentally sustainable, fluorine-free extinguishing agent, addressing ecological concerns [8].

INTELLIGENT DELIVERY SYSTEMS

- *Aerosol Fire Suppressants:* incredibly potent fine-particle aerosols that quickly stop combustion processes.

Aerosol fire suppressants are emerging as a revolutionary technology in fire safety, providing an effective means of controlling and extinguishing fires across various environments (Figure 5). These agents utilize a fine mist or aerosolized particles to rapidly disrupt the combustion process, leading to efficient flame suppression. Unlike traditional fire extinguishing methods, such as water or foam, aerosol suppressants can penetrate hard-to-reach spaces and are particularly effective in enclosed areas, making them suitable for applications in industrial facilities, vehicles, and electronic equipment.

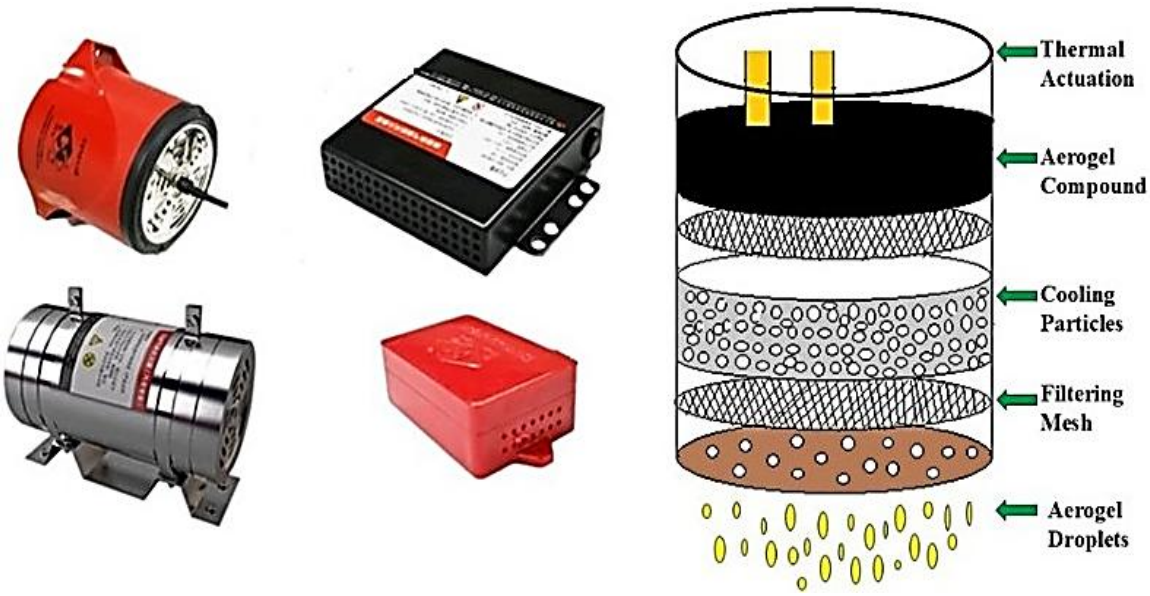

Figure 5. Aerosol fire suppressant system.

The mechanism of aerosol fire suppression primarily involves the release of small solid or liquid particles that interact with the flame, reducing heat and inhibiting the chemical reactions necessary for combustion. These particles can absorb heat, displace oxygen, or interrupt the radical chain reactions that sustain flames. Aerosol fire suppressants are often composed of environmentally friendly materials, such as potassium bicarbonate or ammonium phosphate, which enhances their appeal in terms of safety and environmental impact.

One of the significant advantages of aerosol fire suppressants is their ability to provide rapid and effective suppression with minimal cleanup compared to traditional agents. Aerosol systems are useful for emergency response situations because of their portability and minimal weight. Furthermore, suppressants that work well against a variety of fire classes have been developed because of developments in formulation technology.

- *Robots and Drones:* Automated devices that can locate fires and deliver extinguishing agents to difficult-to-reach locations.

Drones and robots are increasingly being recognized as transformative tools in fire extinguishing mechanisms, offering innovative solutions for improving fire response efficiency and safety (Figure 6). These technologies leverage advanced robotics, AI, and remote sensing capabilities to enhance firefighting operations, particularly in scenarios that are too dangerous for human firefighters. By employing drones and robotic systems, fire departments can significantly improve situational awareness, access hard-to-reach areas, and deliver extinguishing agents more effectively.

Figure 6. Drones and robots in fire-suppressant system.

Accurate evaluation of the fire's location, intensity, and spread is made possible by real-time data on fire dynamics provided by drones fitted with thermal imaging cameras and other sensors. This data is essential for creating efficient firefighting plans and allocating resources as efficiently as possible. Additionally, drones can be deployed to deliver fire suppressants such as water, foam, or powdered extinguishing agents directly to the blaze, facilitating rapid intervention and minimizing collateral damage.

Robotic firefighting systems can operate autonomously or be remotely controlled, enabling them to navigate hazardous environments while performing critical tasks such as extinguishing flames, clearing debris, and securing areas. These robots are often equipped with advanced firefighting tools, including high-pressure water hoses, thermal imaging, and communication systems, allowing them to support human firefighters effectively. The integration of drones and robots into firefighting operations not only enhances safety by reducing the risk to personnel but also improves operational efficiency by enabling faster response times. But there are still issues like legal restrictions, technical constraints, and the requirement for intensive training and cooperation with conventional firefighting techniques.

There is a report on the physical and chemical processes occurring at the seat of a fire during various stages of its development and suppression [9]. The study recorded key parameters, including combustion product temperatures, composition, and flame luminous intensity. The experiments were conducted using a model of a class A fire. The best combinations of technical equipment required and adequate for early fire detection, prompt suppression commencement, and the completion of both combustion and smoldering were determined by the research. Additionally, the minimum required volumes of firefighting liquid (water) needed to effectively suppress combustion were determined. The advantages of incorporating feedback systems during firefighting were also highlighted. These systems enable real-time monitoring of fire behavior, optimizing the consumption of extinguishing agents and reducing fire suppression time. Recommendations for the design of automatic indoor fire suppression systems were made considering the findings. These systems aim to improve firefighting efficiency, enhance safety conditions, and minimize risks to human lives and health.

CHEMICAL INNOVATIONS

- *Nanotechnology:* Use of nanoparticles for enhanced cooling and fire suppression by improving heat absorption and catalytic activity.

Environmentally Friendly Formulations

- Fluorine-free foams to reduce environmental contamination.
- Non-toxic gases (e.g., nitrogen or carbon dioxide mixtures) for suppression with minimal ecological impact.

Hydromagnesite (HM) is a naturally occurring primary carbonate mineral with a broad distribution. To enhance its application potential and exploit its fire-extinguishing capabilities, a novel high-efficiency $KHCO_3$@HM dry powder was developed by coating potassium bicarbonate onto the surface of HM using a dip-coating method [10]. This preparation method introduced a chemical inhibition mechanism, significantly improving the fire-extinguishing efficiency of $KHCO_3$@HM dry powder. A series of tests was conducted to validate the outstanding physical and chemical fire inhibition properties of the material. Specific surface area measurements revealed that $KHCO_3$@HM dry powder had a larger specific surface area (31.405 m^2/g) compared to $NH_4H_2PO_4$ dry powder (12.766 m^2/g). Flowability tests indicated that $KHCO_3$@HM dry powder achieved similar flowability (0.04 g/s) to $NH_4H_2PO_4$ dry powder (0.04 g/s). Fire suppression performance was assessed using local oil basin fire experiments, where $KHCO_3$@HM dry powder demonstrated superior efficiency. Under a driving pressure of 0.2 MPa, $KHCO_3$@HM dry powder reduced fire extinguishing time by 2.2 seconds and required 3.71 grams less powder compared to $NH_4H_2PO_4$ dry powder. The cooling performance of $KHCO_3$@HM dry powder was also superior, achieving a temperature reduction of 208°C within 10 seconds, compared to 157°C for $NH_4H_2PO_4$ dry powder. Additionally, it showed a better smoke suppression effect, reducing smoke concentration to 399 ppm versus 545 ppm for $NH_4H_2PO_4$. The pyrolysis process of $KHCO_3$@HM dry powder contributed to fire suppression by lowering fire temperatures, diluting oxygen concentrations, and capturing free radicals. Furthermore, the resulting pyrolysis products formed a dense oxide film that provided effective heat insulation and asphyxiation. The combined effects of cooling, oxygen dilution, asphyxiation, and chemical inhibition mechanisms in $KHCO_3$@HM dry powder demonstrated excellent overall fire-extinguishing performance, achieving results comparable to $NH_4H_2PO_4$ dry powder.

DYNAMIC FIRE SUPPRESSION

- *Smart Sensors:* These sensors are integrated with Internet of Things (IoT) devices to identify the kind, size, and severity of fires, allowing for accurate agent application.
- *Chemicals:* They modify their suppression qualities (such as cooling, smothering, or chemical interruption) in response to fire characteristics are known as adaptive formulations.

To reduce fire-related casualties, the development of innovative materials that can seamlessly integrate into fire safety strategies is urgently required (Figure 7). In this context, a novel asymmetric "Janus" MXene@Vermiculite/Sodium Alginate (MXene@V/SA) composite paper has been designed, inspired by the "mortar-and-brick" concept. This composite paper is fabricated through a layer-by-layer assembly of two-dimensional (2D) sheets and integrates multiple functionalities, including fire monitoring, early warning, alarm, and rescue. The MXene@V/SA composite paper offers temperature visualization for monitoring and features a self-switching function tailored for smart fire alarm sensor (FAS) systems. When combined with wireless communication technology, it enables rapid fire early warning (~3.6 seconds) and efficient alarm signal transmission. Furthermore, due to the "high temperature shielding effect" of vermiculite and the piezoresistive sensing capabilities of MXene, the composite paper exhibits superior flame retardancy, thermal insulation, and real-time signal monitoring. Notably, the material maintains signal transmission even after exposure to extreme temperatures (~1300°C). In practical applications, the MXene@V/SA composite paper can be used as a wallpaper sensor to detect distress signals from individuals trapped in fires, offering a novel solution for fire rescue and emergency scenarios. This material not only expands the application potential of MXene-based materials in fire safety but also serves as a promising platform for advancing intelligent fire alarm systems and enhancing the accuracy and efficiency of rescue operations [11].

Figure 7. Dynamic fire-suppressant system.

Intelligent sensors with high sensitivity and wireless remote warning capabilities for real-time early fire detection are desperately needed to improve the fire safety of combustible materials used in daily life [12]. Graphene oxide (GO) sheets, chitosan (CS) molecules, and polydopamine (PDA) were shown to combine electrostatically to form an intelligent core-sheath flax-GO/CS/PDA yarn. The yarn leverages the rapid reduction of GO into reduced GO (rGO) under high temperatures, forming a conductive network circuit that enables fire detection. The GO/CS/PDA coating on the flax yarn provides effective thermal and flame protection by preventing heat and oxygen exchange, thus improving the thermal stability and flame retardancy of the flax yarn. Remarkably, with the assembly of just one trilayer, the intelligent core-sheath yarn exhibited a highly sensitive fire warning response time of approximately 3 seconds. The results demonstrated that the yarn not only possessed excellent flame retardancy but also achieved rapid fire detection even at low temperatures (<300°C). Furthermore, the fire alarm signal generated by the intelligent yarn was successfully transmitted to a wireless communication device via Bluetooth. Upon detecting an abnormal temperature, the communication device immediately emitted an alarm sound, ensuring timely alerts. This study provides a novel strategy for achieving ideal fire safety performance and real-time temperature warning response based on GO. Additionally, it broadens the range of possible uses for GO-based networks in wireless sensor warning systems and early fire detection.

The distribution of firefighting equipments (FFEs) carried by unmanned aerial vehicle (UAVs) from firefighting units (FFUs) under the background of multiwave forest fire is also an important factor to control fire effectively [13]. The objective is to allocate the FFEs of each FFU to minimize the sum of the probabilities of each fire site's unsuccessful extinguishment. To solve the multiwave equipment distribution problem of the FFUs, a distributed reinforcement learning algorithm is designed in this paper. In the algorithm, agents cooperate to find the optimal distribution of FFEs based on information exchange, and a local Q-function is established for each agent to find the optimal FFE distribution combination. Simulation results demonstrate the effectiveness of the algorithm.

Multifunctional Agents

- Substances that reduce secondary effects like smoke and the creation of harmful gases, in addition to suppressing flames and preventing reignition.

P-coumaric acid (PCA), ferulic acid (FA), and sinapic acid (SA) were used to create three bio-based propargyl ether thermosetting resins with trans-stilbene cores [14]. These resins showed poor processability because of their high melting points, small processing windows, and substantial exotherms, according to a differential scanning calorimetry (DSC) study. To address this issue, a fourth resin with a more flexible bridging group (PCA-BG) was synthesized from PCA and used as a blending agent. Additionally, PCA was photochemically isomerized into its cis-isomer (cis-PCA), and blends of PCA and cis-PCA were prepared to improve processability. The cross-linked networks derived from these resins demonstrated exceptional thermal stability, with glass transition temperatures (Tg) ranging from 285 to 330°C (as determined by storage modulus) and char yields between 27% and 59% at 1000°C under nitrogen. The processable resin blends benefited from a higher degree of cross-linking, achieved through the structural diversity of the blends, resulting in enhanced thermal properties. The networks' fire resistance was assessed using microscale combustion calorimetry, and their heat release capacity (HRC) values ranged from 43 to 103 J g^{-1} K^{-1}. These values classified the materials as either non-ignitable or self-extinguishing, highlighting their outstanding fire-resistant characteristics. This study demonstrates that bio-based hydroxycinnamic acids, such as PCAs, FAs, and SAs, can serve as versatile platform chemicals for the synthesis of thermally stable and fire-resistant thermosetting networks. The incorporation of photochemical isomerization and blending strategies further enhances the processability and performance of these resins, making them suitable for demanding applications, such as those in the aerospace industry.

Hybrid Systems

- Adding chemical additives to water mist to enhance cooling and oxygen displacement.
- Synergistic formulations that address complex fire types by combining gas, powder, and foam.

Hybrid systems that combine water mist with chemical additives represent a significant advancement in fire extinguishing technology, offering enhanced fire suppression capabilities while addressing the limitations of traditional extinguishing agents. Water mist systems utilize fine droplets of water to cool the fire, reduce heat transfer, and displace oxygen in the combustion zone. When augmented with specific chemical additives, these systems can achieve more effective suppression across a wider range of fire classes, including those involving flammable liquids and electrical fires.

The integration of chemical additives, such as surfactants, foam agents, or extinguishing powders, enhances the performance of water mist by improving its ability to penetrate and extinguish flames. These additives can modify the surface tension of water, allowing for better coverage and increased heat absorption. Furthermore, some additives can chemically interact with the fire, creating a more effective suppression mechanism that targets the combustion process directly.

Hybrid systems are particularly advantageous in environments where traditional firefighting methods may pose risks, such as data centers, industrial facilities, and aircraft hangars. The reduced water usage associated with water mist systems minimizes potential water damage, making them suitable for sensitive equipment and materials. Additionally, the use of environmentally friendly chemical additives ensures that these systems align with sustainability goals.

APPLICATIONS AND BENEFITS OF SMART FIRE EXTINGUISHING AGENTS

- *Industry Safety:* Improved fire safety for high-risk areas like factories, chemical facilities, and oil rigs.
- *Residential Use:* Small, simple-to-install home security systems.
- *Environmental Protection:* Substances are made to have as little of an effect as possible on soil, water, and air ecosystems.
- *Military and Aerospace:* Reliability and efficiency are crucial in high-stakes situations involving fire suppression.

Smart fire extinguishing agents represent a cutting-edge advancement in fire safety technology, incorporating digital innovations and intelligent systems to enhance fire suppression capabilities. These agents are designed to respond dynamically to fire scenarios, utilizing sensors, AI, and data analytics to optimize their effectiveness. The applications of smart fire extinguishing agents span various sectors, including commercial buildings, industrial facilities, transportation, and residential environments, offering tailored solutions to meet diverse fire safety needs.

One of the key benefits of smart fire extinguishing agents is their ability to provide real-time monitoring and assessment of fire conditions. Integrated sensors can detect changes in temperature, smoke, and other indicators of fire, allowing for immediate activation of extinguishing systems. This proactive strategy increases the likelihood of putting out the fire before it gets out of control and reduces response times. Additionally, smart agents can be programmed to adapt their suppression techniques based on the specific characteristics of the fire, ensuring a more efficient and effective response.

The fact that many smart agents have a smaller environmental impact is another important benefit. By utilizing advanced formulations that are often less harmful than traditional extinguishing agents, these systems contribute to sustainability efforts while maintaining effective fire suppression capabilities. Furthermore, the integration of smart technology facilitates better communication and coordination among emergency responders, improving overall firefighting strategies.

The versatility of smart fire extinguishing agents also enables their deployment in challenging environments, such as data centers, museums, and aircraft, where traditional methods may pose risks of damage or ineffectiveness.

CHALLENGES IN THE DEVELOPMENT OF SMART FIRE EXTINGUISHING AGENTS

- *Environmental Regulations:* Complying with guidelines for halogenated agents, such as those established by the Montreal Protocol.
- *Cost:* Creating smart agents that are both economical and incredibly effective.
- *Scalability:* Making sure the system works in a variety of environments and fire situations.

The creation of smart fire extinguishing agents has the potential to transform fire safety in several fields by emphasizing the integration of cutting-edge materials, intelligent technology, and environmental sustainability. An important development in fire safety technology is the creation of smart fire extinguishing chemicals, which are designed to increase effectiveness, lessen their negative effects on the environment, and guarantee their adaptability to a variety of fire situations. However, several challenges impede their development and deployment.

One of the primary challenges is the complexity of designing agents capable of selectively adapting to different fire types, such as Class A (combustible materials), Class B (flammable liquids), and Class C (electrical fires). Achieving multifunctionality while maintaining rapid suppression effectiveness is a significant technical hurdle. Additionally, understanding fire dynamics in real-time requires the integration of sensors and AI systems, which introduces challenges in cost, scalability, and durability under extreme conditions.

Another significant obstacle is environmental concerns. Halons and other conventional fire suppression products have been phased out because they deplete the ozone layer. Developing smart agents that meet modern environmental standards, such as those outlined by the Kyoto and Montreal Protocols, demands innovative materials that are both eco-friendly and effective. Ensuring these agents' dependability and safety in high-stakes situations is another difficulty. Smart extinguishing systems must function flawlessly in a variety of scenarios, including industrial facilities, aircraft, and residential spaces, often under extreme heat, pressure, and contamination. Moreover, regulatory compliance and rigorous testing standards add further complexity to the development cycle.

Economic feasibility is another critical factor. The high cost of research, advanced materials, and integration of AI-driven technologies may limit widespread adoption. Balancing affordability with advanced functionality remains a pressing challenge.

DEVELOPMENT OF SMART FIRE EXTINGUISHING AGENTS

Developing smart fire extinguishing agents entails combining cutting-edge components, features, and technology to produce fire suppression systems that are safer, more effective, and less harmful to the environment. (i) Smart Materials for Extinguishing Agents; (ii) Self-Activating Mechanisms; (iii) Environmentally Friendly Formulations; (iv) Enhanced Suppression Capabilities; (v) Advanced Deployment Systems; (vi) Fire Dynamics Research; and (vii) Safety and Toxicology Studies are the various methods used to develop smart fire extinguishing agents (Figure 8).

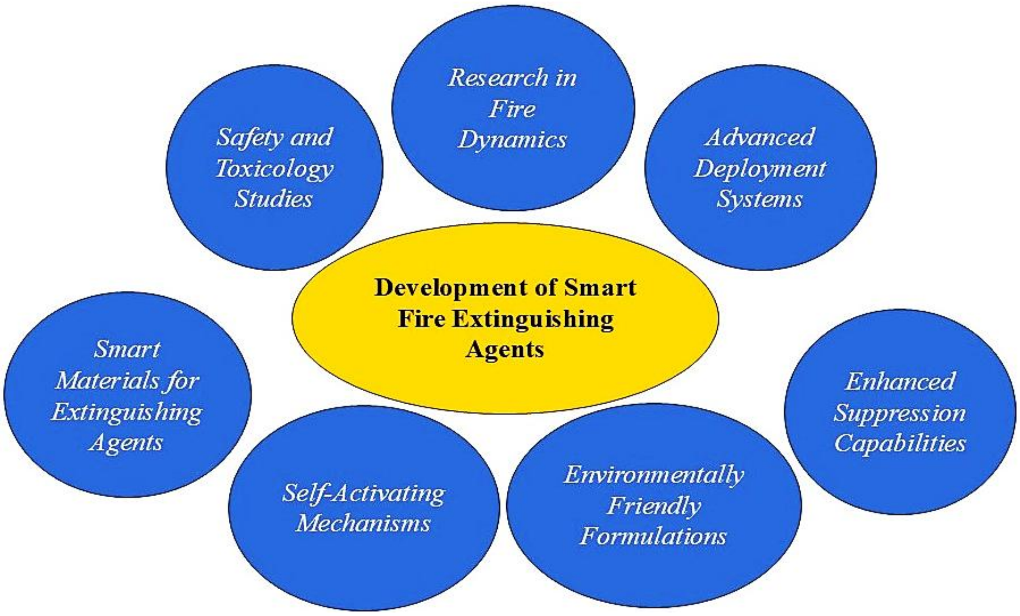

Figure 8. The different approaches to developing the smart fire extinguishing agents.

Smart Materials for Extinguishing Agents

- *PCMs:* These materials efficiently cool the fire zone by absorbing heat and changing their state (from solid to liquid, for example).

- *Intumescent Agents:* Coatings that, when heated, expand to create a barrier that prevents the movement of heat and oxygen.
- *Hydrogels:* Polymers rich in water have the capacity to hold and release a lot of water to quench heat and put out fires.

Self-Activating Mechanisms

- *Nano-Enabled Triggers:* Extinguishing agents with nanosensors integrated into them that can identify high temperatures or certain smoke components and release suppression agents in response.
- *Thermally Responsive Agents:* These agents ensure targeted use and avoid needless deployment by activating only at predetermined temperature thresholds.

A smart fire warning materials and sensors that integrate traditional passive flame-retardant strategies with active fire alarm responses was developed [15]. A thorough and comparative study of these fire warning systems is still missing, though. It offers a thorough explanation of conventional active fire warning sensors, passive flame-retardant materials, and next-generation smart fire warning sensors and materials. The flammability of flammable materials is also examined. A thorough analysis is conducted of the conceptual design, synthesis, characterization, and production techniques of smart fire warning materials. Additionally, the review provides a comparative understanding of the features and mechanisms of different fire warning sensor systems, such as resistance-based sensors, phase/shape-change sensors, thermoelectric-responsive sensors, and color-change observation systems, by evaluating their performance and applications.

The frequent occurrence of building fires highlights the urgent need for materials with exceptional flame retardancy and temperature sensitivity. So, a gelatin/poly(acrylamide-co-acrylic acid)/lithium bromide/sodium phytate/glycerol hydrogel (Gly-GAPL) was synthesized using in situ radical polymerization and solvent exchange techniques [16]. The resulting Gly-GAPL hydrogel demonstrates excellent thermoelectric performance (Seebeck coefficient: 8.66 mV/K), high temperature sensitivity, outstanding mechanical properties, and superior flame retardancy. One of the most remarkable features of Gly-GAPL is its rapid response time, triggering a fire alarm within just 2 seconds of flame exposure. It exhibits strong resistance to ignition and significantly enhances the fire resistance of wood when used as a coating. Additionally, its high transparency, excellent water retention, and strong adhesion make it an ideal flame-retardant coating for a variety of flammable materials. Due to its outstanding thermoelectric properties and temperature sensitivity, Gly-GAPL enables the activation of an early fire-warning system, quickly transmitting alerts to smart devices. So, it presents a novel approach to designing smart flame-retardant materials and expands the application potential of ionic hydrogels in advanced early fire-warning systems.

ENVIRONMENTALLY FRIENDLY FORMULATIONS

- *Bio-Based Foams:* Made from renewable resources, these foams are biodegradable and less harmful.
- *Halogen-Free Compounds:* These compounds effectively reduce Class A, B, and C fires without destroying the ozone layer.
- *Alternatives to Aqueous Film Forming Foams (AFFFs):* Green surfactants can be used in place of conventional AFFFs.

Textile materials are widely utilized due to their desirable properties; however, their inherent flammability poses considerable safety risks, particularly in residential and historical environments. To address these hazards, the incorporation of flame-retardant agents into textiles is crucial for enhancing fire resistance while promoting sustainable practices. A flame-retardant composite made of lignin (L), sodium hypophosphite dihydrate (SHFDH), and nano-graphene oxide (NGO) was applied to cotton–polyester textiles in this study [17]. The limited oxygen index (LOI) test was used to evaluate the flame-retardant effectiveness, and the treated fabrics showed a substantially higher LOI value of 33%, as opposed to only 17% for the untreated materials. TGA and SEM were used to further examine thermal stability and surface morphology. The treated materials demonstrated exceptional flame resistance with a V0 grade in the UL 94 vertical flame test, whereas the untreated fabrics burned at a rate of 110 mm/min. Additionally, the antibacterial properties of the treated fabrics were notably enhanced, with a 15 mm inhibition zone observed, as opposed to no antibacterial activity in the untreated samples. Combustion tests also revealed significant reductions in toxic gas emissions, including decreases of 61% for CO, 50% for CO_2, 54% for SO_2, 60% for NOx, and 66% for NO. These findings demonstrate how well eco-friendly flame-retardant chemicals work to enhance the thermal stability, flame resistance, and antibacterial qualities of textiles. This method lowers harmful pollutants during burning, improving safety while also assisting with sustainability initiatives.

ENHANCED SUPPRESSION CAPABILITIES

- Aerosol fire suppressants are discharged fine particles that, particularly in confined places, interfere with combustion reactions at the molecular level.
- *Multi-Phase Agents:* A blend of solid, liquid, and gaseous agents to provide all-encompassing fire protection.
- *Microencapsulation:* Suppression chemicals are encapsulated in microcapsules that explode when heated or compressed, providing a precise reaction.

There is a report that focuses on the development of multifunctional wearable fabrics, addressing the critical challenge of flammability in wearable textiles [18, 19]. An eco-friendly, asymmetrically structured nylon/cotton (NY/CO) blend fabric was designed through surface modification with phytic acid-induced polyaniline, combined with silver nanowires (AgNWs) and MXene coatings applied to opposite sides, and encapsulated with polydimethylsiloxane (PDMS). The AgNWs coating reduces thermal radiation from the human body to enable radiative heating, while the MXene coating enhances solar absorption for solar-driven heating, ensuring thermal comfort in cold environments. The fabric also provides electrical heating capabilities for heat compensation in the absence of sunlight and demonstrates excellent electromagnetic interference (EMI) shielding, achieving a performance level of 55.6 dB. Enhanced fire safety is achieved as the treated fabric self-extinguishes upon exposure to flame, reducing heat release by 45.9% compared to the untreated NY/CO fabric. Additionally, the treated fabric exhibits significant antibacterial activity against Gram-negative *E. coli* and Gram-positive *S. aureus*, along with a high-water contact angle (WCA) of 130.2°, indicating notable hydrophobicity. This study offers a promising and sustainable approach to the development of eco-friendly, smart wearable fabrics with a balance of superior thermal management, fire safety, EMI shielding, and antibacterial properties.

ADVANCED DEPLOYMENT SYSTEMS

- *Autonomous Drones:* Drones that are outfitted with fire extinguishing agents to put out fires in hard-to-reach places in real time.
- *Smart Sprinkler Systems:* IoT-enabled systems that can locate fire sources and apply extinguishing agents selectively.
- *Robotic Firefighters:* These are robots that can target particular fire zones and carry sophisticated agents.

Conventional fire warning sensors frequently overlook electrical safety and only activate when exposed to flames directly or at reasonably high temperatures. The development of an effective early fire warning sensor that can guarantee circuit safety during flame exposure is crucial to overcoming this constraint. We present a flame-retardant paper that has self-cutting capabilities and a thermosensitive fire alarm reaction. Shape memory thermoplastic polyurethane (SMPU) and MXene are used in the fabrication of the suggested paper using a straightforward electrospinning and vacuum filtration procedure. This content uses the SMPU's shape memory behavior to act as an early fire alert. The SMPU/MXene paper provides stable detection signals and effective early fire warnings when the ambient temperature exceeds the transition temperature of SMPU. Additionally, its electro-activated properties enable it to act as a fuse, protecting the fire alarm system from flame damage. Compared to SMPU paper alone, SMPU/MXene paper demonstrates superior fire-retardant properties, including rapid self-extinguishing performance and significant reductions in the peak heat release rate (pHRR) by 66.0% and the total heat release (THR) by 49.8%. A new method for creating sophisticated fire-alarm sensors and fire safety systems is presented in this paper.

There is a report on the design and development of a cyber–physical system (CPS) use case, utilizing IoT components and wireless sensor network (WSN) elements [20]. The proposed system integrates various hardware components, software elements, computing modules, and communication technologies, resulting in a complex system both structurally and behaviorally. To manage this complexity, a multi-paradigm modeling (MPM) approach is employed throughout the design and development process. It discusses the various phases of development, including requirement analysis, design, modeling and simulation, and implementation. To demonstrate the MPM approach across these phases, the formalism transformation graph and process model (FTG+PM) framework is applied. This framework captures all artifacts and model transformations, providing a clear depiction of the system's data flow and control flow within the PM. Additionally, analysis of the FTG identifies potential improvements to the system, particularly by highlighting critical manual transformations that can be (semi-)automated to enhance efficiency and reduce development effort.

RESEARCH IN FIRE DYNAMICS

Customizing extinguishing agents for contexts, including urban buildings, is made possible by a greater understanding of fire propagation, heat transport, and fuel sources.

- Wooded regions (wildfires, for example).
- Zones for hazardous materials and industry.

Real-time knowledge about fire dynamics is crucial for firefighting, but it is frequently unavailable [21]. To solve this, a machine learning framework is put forth that combines recorded gas temperatures with building geometry to identify fire conditions and forecast temperature changes. Using a pretrained model based on 200 samples from field simulations and 1000 samples from parametric fire models, the framework integrates transfer learning with long short-term memory (LSTM) networks. Predictions based on on-site data can now be made in real time. The framework's excellent accuracy was proved by numerical simulations carried out in portal frame buildings, which achieved 90% prediction accuracy for gas temperatures and over 95% identification of fire situations. Furthermore, when the damage ratio was less than 96%, a technique based on correlation coefficients and standard deviations was able to identify damaged thermocouples with over 30% accuracy. Validation in two real fire scenarios further confirmed the framework's effectiveness, achieving more than 92% accuracy in fire localization and over 89% accuracy in forecasting gas temperatures up to 20 minutes ahead, with computational costs of 2.14 seconds for fire localization and 1.83 seconds for temperature forecasting. The framework also demonstrated robustness to variations in ventilation conditions by applying reliability theory to predict temperatures under changing circumstances. This machine learning-based approach provides firefighters with clear and actionable insights into fire states and dynamics, facilitating smart firefighting and improving response effectiveness.

Because of the growing need for environmental preservation and energy efficiency in contemporary life, personal thermal management stability has become increasingly crucial [22]. A one-step coating preparation method was suggested for creating smart polyester fabrics intended for personal temperature control, drawing inspiration from solid-liquid host-guest materials. A solid–liquid switchable phase-change flame-retardant functional guest is injected into a solid flame-retardant gel, which serves as the host skeleton in this technique. SEM and attenuated total reflectance (ATR) spectroscopy verify that the host–guest structure coating has successfully formed on the polyester fabric surface. Effective personal temperature management of the coated fabric is demonstrated by performance testing in simulated cold and warm situations. Compared to bare polyester fabric, flesh covered in the coated polyester fabric maintains a higher temperature in cold weather. Alternatively, the coated fabric's internal temperature is 5.2°C lower than the uncoated fabric's in warm settings. With a 52.8% decrease in the pHRR) and a horizontal burning rate of 85.7 mm/min, the coated polyester fabric also demonstrates exceptional flame retardancy. Higher levels of graphitization and the inhibition of pyrolysis products are responsible for this improvement. The fabric's mechanical performance, resistance to washing, and water vapor transport are also carefully examined to improve real-world applications. The phase-change flame-retardant polyester fabric with a host–guest structure offers significant potential for personal temperature management applications, including snow rescue, field camping, and outdoor adventure activities.

Tanker ships transport volatile cargo, posing significant risks of fire and explosion. Inert gas systems (IGSs) play a crucial role in mitigating these risks by displacing oxygen in cargo tanks. However, failure of IGS components can result in catastrophic outcomes, including loss of life and marine pollution. There is a report on the systematic methodology that integrates quantitative hazard and operability (HAZOP) analysis with Dempster–Shafer (D-S) evidence theory and fault tree analysis (FTA) to predict and quantify the risks of fire and explosion arising from IGS malfunctions on tanker ships [23]. The proposed approach evaluates failure probabilities and consequences through HAZOP, identifying critical scenarios linked to IGS failures. To address uncertainties and incorporate expert knowledge, D-S evidence theory is applied, enhancing the reliability of the analysis. FTA is utilized to model fault propagation and estimate the likelihood of fire and explosion events associated with identified failure scenarios.

A case study demonstrates the effectiveness of this methodology, highlighting its capability to pinpoint high-risk scenarios and offer actionable insights for improving operational safety. The findings reveal that the risk of fire and explosion due to high oxygen concentrations entering the tank was calculated to be 2.86E-01. Beyond its strong theoretical foundation, it provides the practical contributions for ship crews, inspectors, health, safety, environment, quality (HSEQ) managers, and safety professionals, enabling proactive risk mitigation strategies. By enhancing safety management practices in the maritime industry, the proposed methodology contributes to reducing the risks associated with IGS malfunctions on tanker ships.

SAFETY AND TOXICOLOGY STUDIES

- *Toxicity Levels:* Ensuring agents are safe for humans and the environment during and after use.
- *Residue Analysis:* Studying post-extinguishment residues for environmental and material impacts.

Future Directions

- *AI Integration:* AI-driven fire detection and suppression systems optimize the use of smart agents in real time.
- *Energy-Harvesting Extinguishers:* Extinguishers that use the energy from the fire to power their deployment mechanisms.
- *Collaboration with Materials Science:* Developing next-generation agents with self-healing or adaptive properties.

As crucial to our future paths, the developments in this area have promise for lowering ecological effects, improving safety, and decreasing fire damage (Figure 9). Fire accidents in tunnels are highly destructive and pose severe risks to both trapped individuals and firefighters. In a confined tunnel, fires can escalate quickly and spread between vehicles, making it challenging to predict fire behavior and potential catastrophic events. An intelligent model that uses cutting-edge AI algorithms to forecast temperature distribution, fire information, and crucial events in real time has been developed to address this problem [24]. First, the numerical model is verified using extensive tunnel fire experiments. After validation, 300 transient tunnel fire scenarios are included in a thorough numerical database that includes differences in the initial fire locations, fire sizes, growth rates, spread rates, and ventilation conditions.

This database is then used to train a dual-agent deep learning model that combines a transpose convolutional neural network (TCNN) and LSTM networks. The dual-agent model can forecast transient fire scenarios, such as shifts in fire position and size, up to 30 seconds ahead of time by using input data from on-site temperature sensors. The results demonstrate the model's ability to identify and forecast rapidly evolving fire scenarios, enabling more effective smart firefighting strategies in tunnels.

Figure 9. Future directions.

This study highlights the potential of AI-driven models to improve real-time fire prediction and enhance safety measures in tunnel fire emergencies.

CONCLUSIONS

The development of smart fire extinguishing agents marks a significant leap forward in enhancing fire safety, adaptability, and environmental sustainability. The integration of advanced technologies, such as sensors, AI, and eco-friendly materials, has demonstrated the potential to address complex fire scenarios with precision and efficiency. Despite various challenges, the progress achieved so far provides valuable insights and directions for future advancements. One key conclusion is the importance of developing fire suppression agents that can adapt to a wide range of fire types and environments. Smart agents, equipped with real-time detection and decision-making capabilities, have shown the ability to optimize suppression strategies based on fire class, intensity, and surrounding conditions. This adaptability ensures rapid response and reduces collateral damage, making them invaluable for industrial, residential, and hazardous settings.

Sustainability remains a crucial consideration, and the transition from harmful traditional agents to environmentally safe alternatives has become a priority. Research has revealed that novel, non-toxic materials and innovative chemical formulations can deliver effective fire suppression while adhering to international environmental standards. This shift demonstrates that safety and sustainability are not mutually exclusive but can coexist through technological innovation. Economic and regulatory challenges persist, but advances in cost-effective production methods and successful compliance with rigorous safety standards have paved the way for broader adoption of smart extinguishing agents.

Collaboration among researchers, manufacturers, and policymakers will remain vital to overcoming these barriers.

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