Innovations in Fire Detection and Suppression Systems for Oil Refinery Operations

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Abstract. Oil refineries are prone to high fire hazards that involve volatile chemicals combined with extremely high temperatures in confined spaces. These call for advanced fire suppression and emergency response suppression systems. Whereas the traditional sprinkling of water and foam agents have widely been in use, recent studies through the periods of 2020-2024 indicate their inefficiency in effective control within refinery environs on such grounds as water use, environmental impact and adaptability to hydrocarbon-based fires. Those involving automated detection with IoT and AI in predictive fire monitoring, water mist systems for effective flame cooling and control at minimum water consumption and eco-friendly fluorine-free foam agents contribute less to environmental damage. Hybrid suppression technologies, firefighting drones, robots, VR/AR-based emergency training have developed enhanced safety protocols via faster and more focused responses. However, huge gaps exist in scaling these technologies to sustain extreme temperatures and spatial challenges imposed by refineries, apart from all other maintenance issues, cost-effectiveness and regulatory compliance. This review integrates recent progress, confronts such technologies' effectiveness and economic impact, and proposes future research routes focused on sustainability and autonomy while calling for industrial collaboration and adaptive regulations that support even safer and more resilient refinery operations. In all, sensor-fusion systems have been pointed out as the most effective for oil refineries in terms of fire detection. In contrast, firefighting robots and drone delivery systems remain the most reliable for fire suppression. With continuous research, new technology investment and strategic collaboration, the industry will be assured of improved fire safety, contributing to a more sustainable future toward refinery operation globally.

Keywords: Fire Suppression Technologies; Fire Detection Systems; Oil Refinery Safety; Emergency Response Systems; Automated Fire Detection.

INTRODUCTION

Oil refineries are among the most hazardous industrial environments due to their complex processing units, volatile chemicals, and high-temperature operations. These facilities process large volumes of flammable materials, such as crude oil, gasoline, and other petrochemical products, creating an environment where fires can start easily and spread rapidly. Fires in refineries are often intensified by hydrocarbon-based fuels and high-pressure equipment, leading to severe consequences, including loss of life, environmental pollution, and costly facility damages [1]. Historical refinery incidents underscore the devastating impact of fires and the need for reliable fire safety measures. Given the high-risk nature of refinery operations, fire suppression and emergency response systems are critical for minimising fire-related hazards. While widely used, traditional suppression methods are often insufficient in the refinery context due to their limitations in water usage efficiency, effectiveness against hydrocarbon fires, and environmental impact [2]. Integrating advanced technologies such as automated detection, hybrid suppression systems, and predictive response mechanisms can transform fire safety in these facilities, providing faster, more accurate detection and targeted suppression in high-risk areas [3]. These advancements improve safety and contribute to sustainability goals by reducing environmental contamination from conventional suppression agents, particularly fluorine-based foams [4]. This review aims to consolidate recent advancements in fire detection, suppression and emergency response systems, focusing on innovations from 2020 to 2024 that address the specific challenges of oil refineries. The review evaluates their applicability, effectiveness, and limitations in refinery settings by analysing developments in automated fire detection, eco-friendly foam and water mist systems, and hybrid suppression technologies. Additionally, this paper identifies gaps in current research, such as the adaptability of new technologies to refinery-specific conditions, regulatory compliance, and maintenance requirements. Through a comparative analysis, this review provides industry professionals and researchers with insights into current trends and future directions for enhancing fire safety and emergency response in oil refineries.

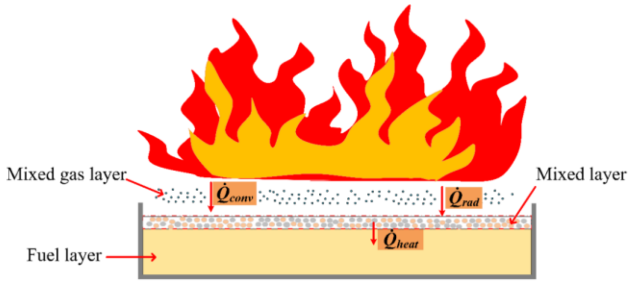

Figure 1 – Heat transfer diagram of fire-extinguishing process [5]

RESULTS AND DISCUSSION

Overview of Traditional Fire Suppression Methods in Oil Refineries

Conventional Fire Suppression Systems and Their Limitations. In oil refineries, traditional fire suppression systems have primarily included water sprinklers, deluge systems, and foam-based extinguishers. Each system has played a vital role in managing fires in industrial environments, particularly for fires fueled by hydrocarbon-based substances [6]. Water-based suppression systems, such as sprinklers and deluge systems, are designed to release large amounts of water over extensive areas, cooling the fire and surrounding materials to reduce heat and slow the spread [7]. However, these systems face limitations in oil refinery settings: hydrocarbons repel water, reducing its effectiveness, and the high-pressure pipelines and equipment create areas where water access is restricted or potentially hazardous. Excessive water use can also increase the risk of chemical runoff, impacting the refinery environment and surrounding ecosystems [8]. Often using aqueous film-forming foam, foam-based suppression systems are more effective in handling hydrocarbon fires because they form a smothering layer over the fuel surface, blocking oxygen and suppressing the fire [9]. Despite this, traditional foams present significant environmental concerns due to perfluoroalkyl and polyfluoroalkyl substances (PFAS), which have long-term ecological impacts and are increasingly subject to regulation. As a result, regulatory bodies and environmental advocates are urging a transition toward fluorine-free foams. Furthermore, conventional foam systems may not efficiently cover fires in enclosed or confined refinery spaces, and their high maintenance needs present logistical challenges [10].

Historical Context and the Need for Modernization. The evolution of fire suppression systems in oil refineries has been significantly influenced by major industrial fire incidents, which revealed weaknesses in traditional firefighting approaches. High-profile refinery fires over the decades have underscored the need for suppression systems that can respond quickly and effectively to contain fires before they escalate [11]. Historically, the fire safety focus in refineries has been on broad water and foam coverage; however, changes in environmental regulations, advancements in fire science, and shifts toward sustainability are pushing the industry to explore and implement advanced, more specialised systems [12]. Modernisation is particularly critical as refineries now handle a broader range of petroleum products and byproducts, some with lower ignition points and higher reactivity. Coupled with the increasing complexity of refinery infrastructure, there is a demand for fire suppression systems that go beyond the capabilities of traditional methods. The integration of advanced suppression technologies such as water mist systems, gas-based suppression, and intelligent detection systems represents a promising path forward in mitigating fire risks while addressing the limitations of conventional methods [13]. The need for environmentally conscious and highly effective systems drives research and industry adoption of innovative technologies, setting a new standard for refinery safety protocols.

While traditional fire suppression systems have served refineries for decades, their limitations in efficacy, environmental sustainability, and adaptability to complex refinery environments underscore the need for innovation. The shift towards advanced fire suppression technologies responds to the unique hazards of modern refineries and the growing focus on environmental responsibility. The following sections will examine recent advancements in fire detection and suppression methods, evaluating their potential to address these longstanding challenges and enhance fire safety standards within the oil refinery sector.

Advancements in Fire Detection Systems

Automated Detection Technologies. Automated fire detection systems have made significant strides in recent years, driven by advancements in sensor technology, machine learning, and network connectivity. Traditional fire detection methods often rely on basic smoke or heat detectors, which may not provide adequate early warning in complex refinery settings where fires can escalate rapidly [14]. Modern automated detection technologies now utilise multi-sensor systems, combining thermal imaging, infrared sensors, and gas detectors to create a layered detection approach that increases accuracy and response speed [15]. Thermal imaging cameras enable continuous monitoring of high-risk areas by detecting temperature variations that can signal the early stages of a fire. This real-time temperature tracking is particularly useful in oil refineries, where certain areas are prone to heat buildup. Infrared sensors can detect flame signatures even through smoke and steam, making them essential for limited visibility environments [16]. Multi-sensor technology allows these systems to verify fire incidents through multiple indicators (e.g. detecting both heat and gas emissions), reducing the risk of false alarms. Multi-sensor systems are also adaptable to refinery-specific hazards, such as leaks or gas buildup, providing an added layer of safety [17]. By enabling quick identification and response, these automated systems minimise the time between fire detection and suppression, significantly reducing the potential for fire escalation.

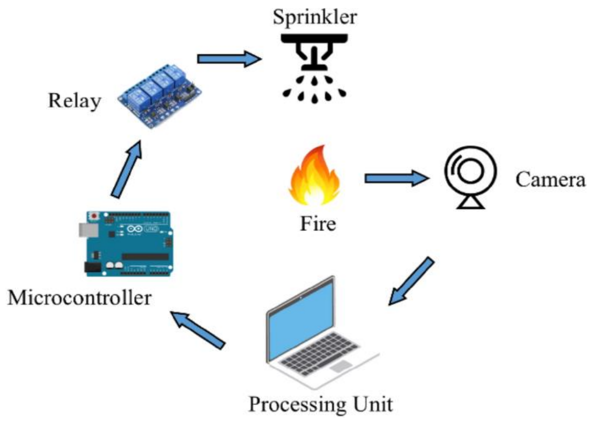

Figure 2 – Automated Fire Detection and Suppression with Computer Vision [18]

Integration with IoT and AI for Predictive Detection. Integrating the Internet of Things (IoT) and Artificial Intelligence (AI) technologies has transformed fire detection systems from reactive to predictive. IoT-enabled sensors can continuously collect and transmit data on temperature, pressure, gas levels, and other parameters within a refinery [19]. AI algorithms analyse this data in real time, detecting anomalies that may precede a fire incident, such as abnormal temperature spikes or gas leaks. By predicting potential fire risks before ignition, these systems enable refinery operators to take proactive measures, such as shutting down equipment, venting gases, or cooling specific areas, thereby preventing fires before they occur [20]. Predictive maintenance is another application of IoT and AI in fire safety, allowing refineries to anticipate equipment failures that could lead to fires. For instance, sensors can monitor the condition of high-risk machinery, and AI models can forecast when certain components are likely to fail. This proactive approach reduces unplanned downtimes and enhances refinery operations' safety and reliability [21].

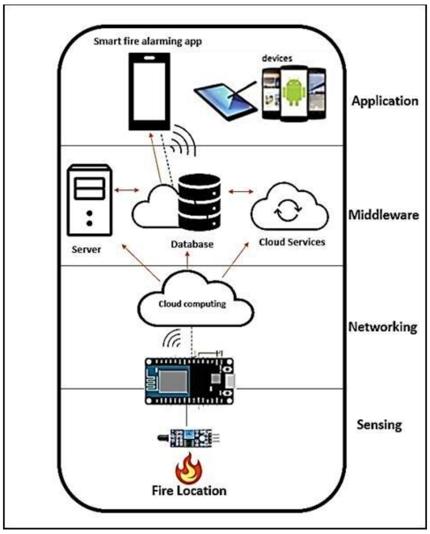

Figure 3 – IoT-Based Fire Alarm System [22]

The recent literature highlights case studies where IoT and AI-enhanced fire detection systems have effectively reduced fire incidents and response times, underscoring the potential of these technologies to revolutionise fire safety in high-risk industrial environments.

Table 1 – Comparative Analysis of the reviewed case studies for the most recent Fire Detection Systems

Technology	Description	Advantages	Limitations	Effectiveness for Oil Pipelines
Sensor Fusion Systems [23]	Combines data from multiple sensors (e.g., heat, smoke, and gas) for improved detection reliability.	Reduces false alarms by cross-verifying sensor data	It can be costly and complex to install and maintain in large areas	Most effective: High reliability in pipeline monitoring, especially in detecting leaks or combustion.
Wireless Sensor Networks (WSNs) [24]	Deploys interconnected sensors to monitor fire-prone areas, transmitting data to central monitoring systems.	Scalable and versatile for remote monitoring, capable of early detection	Dependent on network stability, high maintenance for battery-operated sensors	Highly effective: Ideal for remote pipelines, enabling real-time monitoring and early fire detection.
Machine Learning (ML) Algorithms [25]	ML algorithms, such as Support Vector Machines (SVM) and Decision Trees, analyse sensor data for patterns indicating fire events.	Adaptable to various environments and data types, allows for real-time analysis	Prone to false positives, requires ongoing tuning and data updates	Moderately effective: Can analyse multiple data points; however, false positives could cause interruptions.
Infrared and Ultraviolet Sensing [26]	It detects specific wavelengths associated with combustion and is suitable for environments with	Effective in extreme or smoky environments where visual detection fails	Limited effectiveness in open or brightly lit areas and more costly	Less effective: Suitable for specific pipeline segments but limited by external lighting conditions.

Technology	Description	Advantages	Limitations	Effectiveness for Oil Pipelines
	high fire risks, like industrial zones.			
Image Processing & Deep Learning [27]	Utilises convolutional neural networks (CNNs) to detect fire characteristics such as flames and smoke in real-time from video feeds.	High accuracy in detecting visual fire cues, useful in areas with frequent monitoring like forests	Requires extensive training datasets, high processing power	Least effective: Limited suitability for pipelines where visual fire cues may not always be visible.

Advancements in Fire Suppression Technologies

Water Mist Systems. Water mist systems represent a significant advancement in fire suppression technology, designed to address the specific challenges of fire suppression in confined or equipment-dense refinery spaces. Unlike traditional sprinkler systems, which release large quantities of water, water mist systems disperse fine droplets that cool the flame and surrounding areas more effectively and with minimal water use. This technology is particularly advantageous in oil refineries, where extensive water usage can lead to runoff hazards and is less effective in suppressing hydrocarbon-based fires. The small droplet size allows for rapid cooling and oxygen displacement, making water mist an efficient option for areas with sensitive equipment or limited space. Relevant studies from recent years (2020-2024) have demonstrated that water mist systems can suppress fires in refinery settings faster than conventional sprinklers, with lower environmental impact and reduced water demand, aligning well with sustainability goals [28, 29, 30].

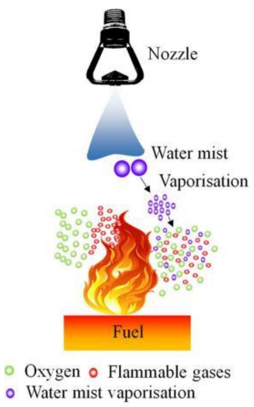

Figure 4 – Heat extraction and water displacement of water mist system [31]

Eco-Friendly Foam Agents. Developing eco-friendly, fluorine-free foam agents has become a priority as environmental concerns over traditional aqueous film-forming foam (AFFF) grow, especially due to harmful PFAS compounds. These new formulations aim to provide the same effectiveness in suppressing hydrocarbon fires while minimising environmental harm. Recent studies indicate that fluorine-free foams can achieve comparable fire suppression performance to AFFF, particularly when used with other fire suppression technologies. Fluorine-free foams reduce the risk of groundwater contamination and comply with emerging environmental regulations, making them suitable for oil refineries that must prioritise fire safety and environmental responsibility. Several case studies document successful trials of eco-friendly foams in real-world refinery environments, underscoring their potential as a viable alternative to traditional PFAS-based foams [32, 33].

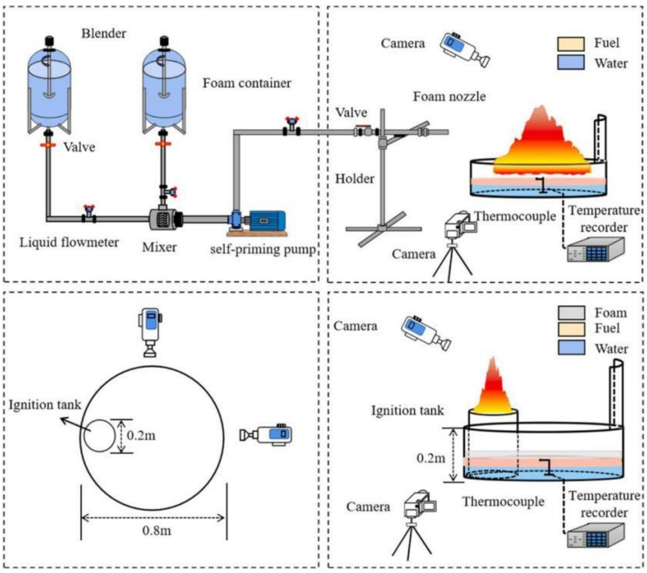

Figure 5 – The gel-glycoside foam fire extinguishing system [34]

Gas-Based Suppression Systems. Gas-based fire suppression systems, such as those using inert gases (e.g. nitrogen and argon) or chemical agents (e.g. clean agents like FM-200), offer targeted fire suppression by displacing oxygen or interrupting the combustion process. In oil refineries, gas-based systems are particularly useful for areas with high electrical equipment density or confined spaces where water or foam use may be impractical. These systems are designed to deploy quickly, minimising fire spread in critical equipment areas and reducing potential downtime. Newer gas-based technologies have improved traditional systems by incorporating sensors and automated controls that optimise gas release, ensuring precise application and reducing waste. Studies from the past few years highlight the effectiveness of gas-based suppression in refinery environments, showing that they can contain fires rapidly without causing additional hazards, such as water damage to sensitive equipment [35].

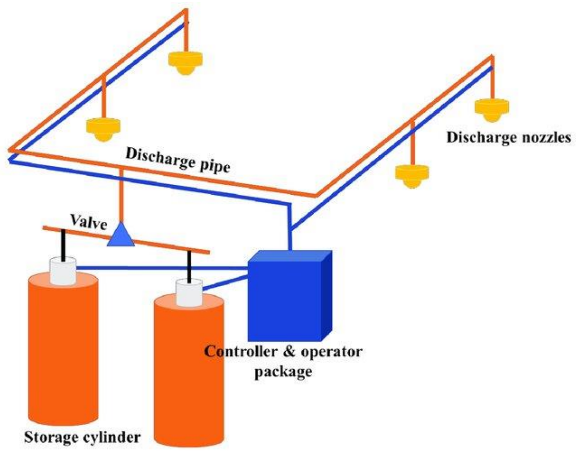

Figure 6 – Schematic diagram of the gaseous fire-suppression system [36]

Hybrid Suppression Systems. Hybrid fire suppression systems combine multiple methods – such as water mist with gas agents or foam with water – to create a comprehensive solution capable of handling a broader range of fire scenarios. These systems allow refineries to deploy tailored responses based on the specific characteristics of different fire-prone areas, making them particularly valuable in facilities with diverse operational zones and fire hazards. For instance, water mist and gas combinations offer cooling and oxygen displacement in equipment-dense areas, while foam and mist systems provide effective coverage for hydrocarbon spills. Hybrid systems are emerging as a flexible solution in refinery safety, allowing operators to adapt to various fire scenarios dynamically. Recent research highlights their potential to reduce response times and increase suppression efficacy in complex fire incidents [37].

Innovations in Delivery Mechanisms: Robotics and Drones. The deployment of robotics and drones for fire suppression has introduced a new level of adaptability and precision in responding to refinery fires. Firefighting robots equipped with heat-resistant materials and thermal cameras can operate in high-risk areas that are unsafe for personnel, providing targeted suppression and real-time data to inform emergency responses. Drones equipped with foam or gas suppressant delivery systems are increasingly being used for aerial firefighting, especially in areas of refineries that are hard to reach or highly congested. These technologies enhance situational awareness, enabling operators to remotely assess and address fire incidents. Research has demonstrated that robotic and drone systems can significantly reduce fire suppression response times, prevent escalation, and provide invaluable support to on-site personnel during complex fire emergencies [38]. Recent advancements in fire suppression technologies, including water mist, eco-friendly foam agents, gas-based systems, hybrid solutions, and robotics, have elevated fire safety standards in oil refineries. Each technology addresses specific refinery challenges, such as water efficiency, environmental impact, confined space adaptability, and high equipment density. Together, they form a multi-layered approach to fire suppression, aligning with the industry's shift toward sustainability and operational safety. The following sections will analyse these advancements' effectiveness, cost considerations, and environmental implications, providing a holistic view of their practical applications in oil refinery safety management.

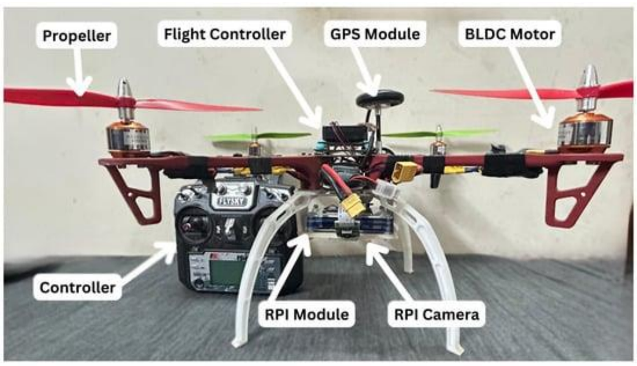

Figure 7 – Hardware design of the proposed fire detection drone with various components [39]

Table 2 – Comparative Analysis between the most recently reviewed Fire Suppression Systems

Technology	Mechanism	Ecological Impact	Oil Pipeline Suitability
Water Mist Systems	It uses finely atomised water particles to cool flames and displace oxygen, effectively suppressing fires.	Moderate, low water usage.	Effective for smaller fires; potential challenges with large-scale pipeline fires.
Eco-Friendly Foam Agents	Biodegradable foams that create a barrier to prevent oxygen from reaching the fire source.	High, due to its biodegradable nature.	It is very effective for pipelines due to rapid deployment and wide area coverage.
Gas-Based Suppression	Uses inert or halocarbon gases to suppress fire by displacing oxygen.	Variable: some agents have low environmental impacts.	Moderate suitability; requires confined spaces, can be less effective in open pipeline areas.
Hybrid Suppression Systems	Combines water mist with inert gases for effective suppression with minimal damage.	High: combines low water use with inert gas benefits.	Adaptable to pipeline environments but depends on the integration of multiple suppression agents.
Robotics & Drones	Remote-controlled units equipped with suppression agents or detection systems for hazardous areas.	It depends on the system; it is generally eco-friendly.	It is highly effective and allows safe access to hazardous areas, ideal for inspection and suppression in remote pipelines.

Comparative Analysis of Fire Suppression and Detection Methods

Effectiveness and Efficiency of Advanced Systems. The effectiveness of fire suppression and detection technologies is measured by their ability to detect, respond to, and control fires in oil refineries swiftly and with minimal resource use. Recent comparative studies have shown that automated detection systems integrated with AI and IoT offer significantly faster response times than traditional systems, as they can simultaneously monitor multiple risk indicators and alert personnel before fires escalate. Multi-sensor systems, which combine thermal imaging, infrared, and gas detection, have proven more reliable in identifying early fire signals in high-risk areas than single-sensor models. Similarly, water mist systems and eco-friendly foam agents are noted for their rapid-fire suppression capabilities with minimal water and environmental impact, showing a clear improvement over traditional sprinklers and PFAS-based foams. For instance, water mist technology requires less water to cool flames, reducing the potential for runoff and contamination. Gas-based suppression has also demonstrated high efficiency in confined spaces, where traditional suppression agents might be less effective due to access limitations or equipment sensitivity.

Economic Considerations and Cost-Effectiveness. Adopting advanced fire suppression and detection technologies requires substantial upfront investment, which can be a barrier for many refineries. However, when evaluating the cost-effectiveness of these systems, factors such as reduced downtime, minimised equipment damage, and lower maintenance costs are crucial. Automated detection systems with predictive maintenance capabilities reduce unplanned shutdowns and extend equipment lifespan, yielding long-term savings. Although eco-friendly foam agents and water mist systems can be more expensive than traditional methods, they decrease environmental cleanup costs, reduce regulatory fines related to PFAS pollution, and contribute to sustainability targets, which are increasingly valuable in the current regulatory environment. Hybrid systems also present a favourable economic case by allowing refineries to optimise fire suppression response based on specific scenarios, potentially reducing the volume of suppression agents needed. Cost-benefit analyses from recent literature suggest that, despite higher initial costs, advanced systems can offer a positive return on investment by enhancing operational resilience and minimising financial risks associated with fire incidents.

Environmental Impact and Compliance with Regulations. Environmental sustainability is critical in adopting new fire suppression and detection technologies, as traditional methods often involve chemicals or high water use with lasting ecological effects. Regulatory bodies worldwide are phasing out PFAS-containing foams due to their harmful effects on groundwater and the environment. Consequently, fluorine-free foam agents are gaining traction as an environmentally responsible alternative, aligning with regulatory demands for sustainable practices in fire safety. Similarly, water mist systems, which use smaller volumes of water, help refineries meet sustainability targets by reducing water consumption and minimising the risk of toxic runoff. Gas-based suppression systems align with environmental goals, as they do not produce harmful residues and can be safely deployed in sensitive areas. Adopting IoT-enabled predictive detection systems contributes indirectly to environmental goals by preventing fire incidents, reducing the likelihood of spills, and minimising equipment damage. Compliance with environmental regulations reduces the risk of fines and strengthens a refinery's social license to operate, showcasing a commitment to sustainable practices.

Safety and Operational Challenges. While advanced fire suppression and detection systems offer numerous benefits, they also present unique operational and safety challenges. For instance, water mist and gas-based suppression systems require specialised installation and maintenance procedures to ensure reliable operation, as incorrect setup could compromise their efficacy. Furthermore, integrating AI-driven predictive detection systems introduces cybersecurity risks, as connected devices may be vulnerable to unauthorised access or malfunctions. Hybrid systems, while flexible, can be complex to operate and may require highly trained personnel to manage the varied responses effectively. Another consideration is the risk associated with drone and robotic fire suppression systems. At the same time, they enhance firefighting capabilities. However, emerging technologies may face operational limitations in extreme refinery environments, such as high temperatures or exposure to corrosive chemicals. Literature from 2020-2024 emphasises the need for rigorous training, regular system maintenance, and cybersecurity protocols to address these challenges and ensure the safe deployment of advanced fire suppression and detection technologies.

Comparative Summary and Key Findings. The comparative analysis of fire suppression and detection methods reveals that recent technological advancements provide enhanced efficiency, environmental sustainability, and adaptability to the unique hazards of oil refineries. Automated detection systems, eco-friendly foams, and hybrid suppression solutions significantly improve over traditional methods, particularly in minimising environmental impact and achieving faster response times. Despite higher initial costs, these systems prove cost-effective over time due to reduced maintenance needs, regulatory compliance benefits, and potential for long-term operational savings. However, successfully adopting these technologies hinges on overcoming operational challenges, including installation complexities, cybersecurity risks, and training requirements. In summary, advanced fire suppression and detection systems offer robust improvements in refinery safety, aligning with industry shifts toward sustainability and resilience. The subsequent section will address the remaining technical and regulatory obstacles and provide recommendations for enhancing fire safety practices within the oil refinery sector.

Challenges and Limitations in Fire Suppression and Detection Technologies

Technical Challenges in System Integration. Despite the significant advancements in fire suppression and detection technologies, their integration into existing refinery infrastructure remains a substantial technical challenge. Many refineries still rely on legacy systems that were not designed to accommodate the complexities of modern technologies such as IoT-enabled sensors or AI-driven predictive analytics. Integrating new fire detection systems with older equipment often requires substantial modifications, which can be costly and time-consuming. For example, incorporating multi-sensor detection systems or water mist suppression technologies into a refinery with limited access or confined spaces can lead to complex installation and calibration processes. Additionally, some refinery areas may lack sufficient connectivity infrastructure to support real-time data transmission from sensors to central monitoring systems, hindering the effectiveness of automated systems. Addressing these integration hurdles is crucial to ensuring that fire safety technologies function optimally within oil refineries' diverse and often challenging environments.

System Reliability and False Alarms. While modern fire detection systems offer enhanced sensitivity and early detection capabilities, false alarms remain a concern, particularly in environments like refineries where smoke, heat, or chemical vapours can trigger sensors. False positives can lead to unnecessary downtime, unnecessary activation of suppression systems (which may cause equipment damage or downtime), and even safety risks if personnel respond to non-existent threats. Technologies such as AI-driven predictive detection systems are intended to reduce the occurrence of false alarms by analysing patterns and anomalies. Yet, these systems still face challenges distinguishing between genuine fire hazards and environmental factors that mimic fire-like symptoms. Addressing these reliability issues is vital to the continued adoption of advanced detection systems. Research from 2020-2024 highlights the development of more robust machine learning algorithms and sensor fusion techniques that aim to reduce false alarms and improve the accuracy of fire detection systems. However, challenges remain in achieving consistent reliability across varied operating conditions.

High Initial Costs and Financial Barriers. One of the primary obstacles to the widespread adoption of advanced fire suppression and detection technologies is the high initial investment required for implementation. For refineries operating on tight budgets or prioritising immediate operational demands, the upfront costs of systems like AI-integrated detection, robotic firefighting solutions, or hybrid suppression systems may be prohibitive. Although these systems offer long-term savings regarding reduced operational downtime, maintenance costs, and improved safety, the financial barrier remains a key concern. Refineries may face challenges justifying these investments to stakeholders, particularly when the financial returns are not immediately apparent. However, recent studies suggest that the long-term economic benefits, such as regulatory compliance, enhanced safety records, and reduced environmental impact, may outweigh the initial costs. The challenge lies in balancing these financial considerations with the need for cutting-edge fire safety technologies, particularly in regions or refineries with limited budgets or fewer financial resources.

Regulatory and Industry Standards Compliance. The regulatory landscape surrounding fire suppression and detection technologies constantly evolves, particularly with increasing pressure on industries to meet environmental and safety standards. Refineries must navigate a complex web of local, national, and international regulations, which can be challenging, especially when new technologies are introduced. For instance, fluorine-free foam agents are being phased in as replacements for PFAS-based foams due to growing environmental concerns over water contamination. However, transitioning to these new foam formulations can involve complex regulatory compliance and testing. Similarly, integrating AI-based fire detection systems may require refineries to ensure these technologies meet specific data security and system reliability regulatory standards. Moreover, refineries operating in multiple jurisdictions must adhere to differing fire safety regulations, adding complexity to implementing standardised technologies across all sites. The evolving nature of safety regulations and the need for continuous compliance can slow the adoption of advanced technologies despite their clear benefits.

Cybersecurity Risks and Vulnerabilities. As fire detection and suppression systems become more interconnected with IoT and AI technologies, they introduce potential cybersecurity risks. The growing reliance on real-time data transmission and cloud-based systems for monitoring and controlling fire safety introduces vulnerabilities to hacking, data breaches, and system malfunctions. Refineries may face threats from cyber-attacks aimed at manipulating fire safety systems, potentially leading to disastrous consequences, such as delayed responses to real fire incidents or the inadvertent activation of suppression systems. As refineries adopt more advanced technologies, cybersecurity must be prioritised, with investment in secure network infrastructure, encryption protocols, and continuous monitoring of system integrity. Interacting with industrial control systems with IT networks creates a complex environment where cybersecurity must be a core consideration for operational integrity and safety.

Limited Research on Long-Term Effectiveness and Maintenance. Although significant progress has been made in developing advanced fire suppression and detection systems, there is still limited research on their long-term effectiveness and maintenance needs. Many studies focus on the initial deployment and operational efficiency of new technologies. Still, there is a need for further research into how these systems perform over time, particularly in the demanding environments of oil refineries. For example, how water mist systems hold up in environments with high temperatures, corrosive chemicals, or dust accumulation is not fully understood.

Additionally, some advanced suppression systems require specialised maintenance and technical expertise, which may not always be available locally, leading to potential challenges in upkeep. Further research into these systems' durability, lifecycle performance, and long-term maintenance costs would benefit refineries planning to adopt these technologies as safety protocols. Several challenges, including integration issues with legacy systems, reliability concerns such as false alarms, high upfront costs, and the complexity of meeting evolving regulatory requirements, impede the deployment of advanced fire suppression and detection technologies in oil refineries.

Additionally, cybersecurity risks and the need for further research into long-term system performance are crucial barriers to full adoption. While these technologies promise significant improvements in fire safety, addressing these challenges will require continuous investment, innovation, and industry-wide collaboration. As refineries navigate these limitations, there is a clear opportunity for further research and development to optimise fire safety solutions and ensure that they meet operational and regulatory requirements while maintaining safety and cost-effectiveness. The final section will explore potential future directions and recommendations to overcome these challenges and enhance fire safety practices within the oil and gas sector.

Future Directions and Recommendations

Integration of Artificial Intelligence and Machine Learning in Fire Safety Systems. As fire detection and suppression technologies evolve, integrating Artificial Intelligence (AI) and Machine Learning (ML) offers immense potential for refining fire safety practices in oil refineries. AI-powered systems can analyse large volumes of data from sensors, environmental conditions, and operational processes to detect patterns indicating early signs of fire hazards. This real-time predictive capability can allow faster and more accurate detection of fires or malfunctions before they escalate into full-blown emergencies. AI can also optimise fire suppression response by tailoring the amount and type of suppression agents based on the specific characteristics of the fire, the environment, and available resources. Future research should focus on refining these AI and ML models to ensure their reliability and accuracy in dynamic and complex refinery environments. Moreover, adaptive learning algorithms could help these systems continuously improve their performance by learning from past incidents and adjusting their parameters to minimise false positives and optimise response times.

Development of Smart Fire Suppression and Detection Systems. The concept of smart fire suppression and detection systems, which combine sensors, AI, IoT connectivity, and cloud computing, will drive future advancements in fire safety technologies. These systems can offer integrated solutions, providing real-time monitoring, predictive maintenance, and automated fire response in oil refineries. A major area for future exploration is enhancing the interconnectivity of these systems, enabling them to share information across refinery operations for a more cohesive safety strategy. For instance, IoT-enabled devices can continuously monitor temperature, humidity, and gas concentrations, while cloud-based analytics platforms can process this data remotely to generate real-time insights and alerts. This seamless communication will enable predictive fire detection and precise activation of suppression systems. Future innovations should focus on ensuring the interoperability of such systems across different refinery platforms and developing more user-friendly interfaces for refinery operators.

Sustainable and Eco-Friendly Fire Suppression Solutions. The oil and gas industry is increasingly focused on reducing its environmental footprint, and this shift is extending to fire suppression technologies. Fluorine-free foam agents and water mist systems are promising eco-friendly alternatives that reduce toxic chemicals and excessive water use. However, further research is needed to improve the effectiveness and cost-effectiveness of these green technologies to ensure they can replace traditional methods in a wider range of fire scenarios. Future innovations could focus on developing biodegradable foam agents or natural fire suppression fluids that are both efficient and safe for the environment. Additionally, further advancements in zero-water or low-water suppression technologies are necessary to address challenges posed by water scarcity in certain regions or refineries. Exploring more sustainable options will help oil refineries meet their safety and environmental goals.

Advancements in Robotics and Autonomous Systems for Fire Suppression. The role of robotics and autonomous systems in fire suppression is poised to expand, offering significant benefits in terms of safety, efficiency, and precision. Firefighting robots and drones with sensors, cameras, and suppression equipment can reach hazardous and hard-to-access areas within a refinery where human presence is restricted or dangerous. Future developments should focus on improving the autonomy of these systems, enabling them to operate independently in complex environments while making real-time decisions about fire suppression strategies. Additionally, integrating robotics with AI-driven analysis could allow for faster and more accurate identification of fire risks, with robots automatically deploying the appropriate suppression techniques. Advances in battery technology and power autonomy for drones and robots will be essential to ensure these systems can function effectively over extended periods without requiring frequent recharging or maintenance.

Continuous Monitoring and Remote Control Capabilities. The future of fire safety in refineries will increase reliance on remote monitoring and control capabilities. Advances in wireless communication, 5G networks, and satellite communication systems will enable real-time remote monitoring of fire suppression and detection systems from centralised control rooms or even remote locations. This will enhance the ability of refinery operators to manage fire safety on a global scale, particularly in large refineries or those with multiple facilities. In addition, continuous monitoring systems will allow for the early detection of equipment malfunctions or fire hazards before they escalate. These systems can be integrated with predictive maintenance features, alerting operators to potential issues before they cause equipment failure or safety risks. The next frontier of fire safety technologies will involve further development of seamless, highly reliable communication platforms that instantly relay vital data to operators and first responders.

Enhanced Training and Simulation Platforms. Training and simulation platforms will be critical in ensuring that advanced fire suppression and detection systems are used to their fullest potential. Virtual reality (VR) and augmented reality (AR) technologies can create realistic fire emergency scenarios for training refinery personnel. These platforms can simulate various fire scenarios, allowing operators to practice responding to incidents in a safe and controlled environment. Additionally, AI-driven simulations can help evaluate different suppression methods and response strategies, allowing staff to learn optimal fire response protocols based on real-world data. Future efforts should focus on developing interactive training tools that incorporate both virtual and real-life elements to prepare employees for emergencies in a way that enhances their skills and confidence.

Collaboration Between Industry and Research Institutions. There needs to be stronger collaboration between the oil and gas industry, research institutions, and technology developers to advance fire safety technologies. Industry-specific research on real-world applications of emerging fire suppression technologies will help bridge the gap between laboratory results and field deployment. Partnerships can facilitate the development of solutions tailored to the specific needs of refineries, addressing issues like system integration, scalability, and cost. Joint efforts will also promote cross-disciplinary innovations, where advancements in materials science, data analytics, and environmental engineering can be leveraged to improve fire safety technologies. Collaborative initiatives will foster the creation of standards for fire safety technologies that can be adopted globally across the industry.

Policy and Regulatory Advancements. In line with technological advancements, policy and regulatory frameworks must evolve to ensure the safe implementation and operation of advanced fire suppression and detection systems. Governments and regulatory bodies should work with industry stakeholders to develop standards for emerging technologies, ensuring they meet safety, environmental, and operational requirements. Updated regulations should also account for integrating eco-friendly fire suppression solutions and the increased use of digital technologies like AI, IoT, and autonomous systems. By establishing clear, updated guidelines and standards, regulatory bodies can help ensure that fire safety measures are cutting-edge but also safe, compliant, and cost-effective. The future of fire suppression and detection in oil refineries is bright, with numerous innovative technologies poised to transform fire safety practices. As the industry continues to address system integration challenges, environmental impact, and cost, adopting AI, robotics, eco-friendly solutions, and smart systems will become increasingly important. Developing advanced training tools and collaborative partnerships will further enhance the industry's ability to deploy these technologies effectively. By focusing on research, innovation, and regulatory alignment, the oil and gas sector can look forward to a safer, more sustainable future where fire hazards are managed with precision, efficiency, and minimal environmental impact.

CONCLUSIONS

This review has examined the significant advancements and emerging fire suppression and detection technologies trends within the oil refinery sector. Over the past few years, substantial progress has been made in improving fire safety by developing eco-friendly fire suppression agents, AI-powered detection systems, and robotic firefighting solutions. Integrating smart systems using IoT and cloud computing is poised to revolutionise how refineries manage fire hazards by providing real-time monitoring, early detection, and automated response. Technologies such as water mist systems, fluorine-free foams, and hybrid suppression techniques show promise in reducing the environmental impact of fire safety practices. However, while these innovations offer substantial benefits in terms of efficiency and sustainability, challenges such as high implementation costs, integration issues, and false alarm risks still hinder widespread adoption. The increasing complexity of fire safety systems and the cybersecurity risks associated with their connectivity also require further research and attention. The oil and gas industry faces increasing pressure to enhance safety measures while minimising environmental impacts, making adopting advanced fire suppression and detection systems a safety imperative and an environmental and regulatory necessity. The integration of AI and robotics into fire safety measures offers the potential for greater accuracy, faster response times, and improved safety, while sustainable suppression solutions help align fire safety practices with the industry's environmental goals. With a focus on integrating new technologies into refinery infrastructure and ensuring long-term cost-effectiveness, these advancements can play a critical role in reducing the risks and consequences of fire-related incidents in refineries. However, the transition to these advanced technologies is not without challenges. The high initial costs, system integration complexities, and the need for specialised training present significant barriers. To overcome these, refineries must adopt a holistic approach that includes long-term planning, industry collaborations, and a commitment to research and development.

Additionally, the evolving regulatory landscape will require refineries to remain adaptable and proactive in adopting new fire safety technologies. The fire safety landscape in oil refineries is undergoing a profound transformation, driven by technological advancements, environmental concerns, and the need for enhanced operational safety. As technologies such as AI, IoT, robotics, and sustainable suppression agents continue to evolve, they offer the potential to significantly reduce the occurrence and severity of fire incidents in refineries. However, there remains a need for ongoing innovation to address the existing gaps and challenges in the industry. The next phase of fire safety evolution in refineries will require collaboration between industry stakeholders, researchers, and policymakers to ensure that these new technologies are effectively integrated into existing infrastructures, meet regulatory standards, and align with the broader sustainability goals of the oil and gas industry. The focus should be on creating scalable, adaptable, and cost-effective fire safety systems that improve personnel safety and refinery operations' environmental footprint. In conclusion, the potential for advancements in fire suppression and detection technologies to transform safety practices in oil refineries is substantial. With continued research, investment in new technologies, and strategic collaboration, the industry can enhance its fire safety measures, contributing to a safer, more sustainable future for refinery operations worldwide.

REFERENCES

1. Al-Moubaraki, A. H., & Obot, I. B. (2021). Corrosion challenges in petroleum refinery operations: Sources, mechanisms, mitigation, and future outlook. *Journal of Saudi Chemical Society, 25*(12), 101370. doi: 10.1016/j.jscs.2021.101370

2. Gholamizadeh, K., Alauddin, M., Aliabadi, M. M., Soltanzade, A., & Mohammadfam, I. (2022). Comprehensive Failure Analysis in Tehran Refinery Fire Accident: Application of Accimap Methodology and Quantitative Domino Effect Analysis. *Fire Technology, 59*(2), 453–472. doi: 10.1007/s10694-022-01348-6

3. Adeoye Taofik Aderamo, Henry Chukwuemeka Olisakwe, Yetunde Adenike Adebayo, & Andrew Emuobosa Esiri. (2024). AI-Driven HSE management systems for risk mitigation in the oil and gas industry. *Comprehensive Research and Reviews in Engineering and Technology, 2*(1), 001–022. doi: 10.57219/crret.2024.2.1.0059

4. Hossain, F., Dennis, N. M., Subbiah, S., Karnjanapiboonwong, A., Guelfo, J. L., Suski, J., & Anderson, T. A. (2022). Acute Oral Toxicity of Nonfluorinated Firefighting Foams to Northern Bobwhite Quail (Colinus virginianus). *Environmental Toxicology and Chemistry, 41*(8), 2003–2007. Portico. doi: 10.1002/etc.5398

5. Yan, L., Wang, N., Guan, J., Wei, Z., Xiao, Q., & Xu, Z. (2023). Comparative Study of the Suppression Behavior and Fire-Extinguishing Mechanism of Compressed-Gas Aqueous Film-Forming Foam in Diesel Pool Fires. *Fire, 6*(7), 269. doi: 10.3390/fire6070269

6. Zhang, Z., Larranaga, A. S., & Wang, Q. (2024). Liquefied natural gas storage and transmission. *Advances in Natural Gas: Formation, Processing, and Applications. Volume 6: Natural Gas Transportation and Storage*, 51–80. doi: 10.1016/b978-0-443-19225-8.00009-3

7. Söderholm, D. (2023). *Fire Safety in Hydrogen Processing Facilities-Design Considerations*. Retrieved from https://www.theseus.fi/bitstream/handle/10024/815753/S%c3%b6derholm_Dick.pdf?sequence=2&isAllowed=y

8. Marcoux, L., Mullin, E., & Tang, D. (2023, April). *Water Contamination from Fire Events*. Retrieved from https://digital.wpi.edu/pdfviewer/08612s29c

9. Puchovsky, M., & Simeoni, A. (2020). *The Feasibility of Protecting Residential Structures from Wildfires using a Fixed Exterior Fire Fighting System*. Retrieved from https://digital.wpi.edu/pdfviewer/6q182n72c

10. Garg, S., Kumar, P., Mishra, V., Guijt, R., Singh, P., Dumée, L. F., & Sharma, R. S. (2020). A review on the sources, occurrence and health risks of per-/poly-fluoroalkyl substances (PFAS) arising from the manufacture and disposal of electric and electronic products. *Journal of Water Process Engineering, 38*, 101683. doi: 10.1016/j.jwpe.2020.101683

11. Kuznetsov, G., Kopylov, N., Sushkina, E., & Zhdanova, A. (2022). Adaptation of Firefighting Systems to Localization of Fires in the Premises: Review. *Energies, 15*(2), 522. doi: 10.3390/en15020522

12. Omidvar, B., & Mohamadzadeh, B. (2023). Fire event in oil, gas, and petrochemical industries. *Crises in Oil, Gas and Petrochemical Industries*, 155–174. doi: 10.1016/b978-0-323-95154-8.00015-3

13. Panda, S., Mehlawat, S., Dhariwal, N., Kumar, A., & Sanger, A. (2024). Comprehensive review on gas sensors: Unveiling recent developments and addressing challenges. *Materials Science and Engineering: B, 308*, 117616. doi: 10.1016/j.mseb.2024.117616

14. Al-Ruzouq, R., Gibril, M. B. A., Shanableh, A., Kais, A., Hamed, O., Al-Mansoori, S., & Khalil, M. A. (2020). Sensors, Features, and Machine Learning for Oil Spill Detection and Monitoring: A Review. *Remote Sensing, 12*(20), 3338. doi: 10.3390/rs12203338

15. Khan, F., Xu, Z., Sun, J., Khan, F. M., Ahmed, A., & Zhao, Y. (2022). Recent Advances in Sensors for Fire Detection. *Sensors, 22*(9), 3310. doi: 10.3390/s22093310

16. Radi, M. A., Li, P., Boumaraf, S., Dias, J., Werghi, N., Karki, H., & Javed, S. (2024). AI-Enhanced Gas Flares Remote Sensing and Visual Inspection: Trends and Challenges. *IEEE Access, 12*, 56249–56274. doi: 10.1109/access.2024.3389979

17. Sharma, A., Kumar, R., Kansal, I., Popli, R., Khullar, V., Verma, J., & Kumar, S. (2024). Fire Detection in Urban Areas Using Multimodal Data and Federated Learning. *Fire, 7*(4), 104. doi: 10.3390/fire7040104

18. Mondal, M. S., Prasad, V., Kumar, R., Saha, N., Guha, S., Ghosh, R., Mukhopadhyay, A., & Sarkar, S. (2023). Automating Fire Detection and Suppression with Computer Vision: A Multi-Layered Filtering Approach to Enhanced Fire Safety and Rapid Response. *Fire Technology, 59*(4), 1555–1583. doi: 10.1007/s10694-023-01392-w

19. Giannakidou, S., Radoglou-Grammatikis, P., Lagkas, T., Argyriou, V., Goudos, S., Markakis, E. K., & Sarigiannidis, P. (2024). Leveraging the power of internet of things and artificial intelligence in forest fire prevention, detection, and restoration: A comprehensive survey. *Internet of Things, 26*, 101171. doi: 10.1016/j.iot.2024.101171

20. Dash, A., Bandopadhay, S., Samal, S. R., & Poulkov, V. (2023). AI-Enabled IoT Framework for Leakage Detection and Its Consequence Prediction during External Transportation of LPG. *Sensors, 23*(14), 6473. doi: 10.3390/s23146473

21. Kochkov, D., Smith, J. A., Alieva, A., Wang, Q., Brenner, M. P., & Hoyer, S. (2021). Machine learning–accelerated computational fluid dynamics. *Proceedings of the National Academy of Sciences, 118*(21). doi: 10.1073/pnas.2101784118

22. Al Hasani, I. M. M., Kazmi, S. I. A., Ali Shah, R., HASAN, R., & Hussain, S. (2022). IoT based Fire Alerting Smart System. *Sir Syed University Research Journal of Engineering & Technology, 12*(2), 46–50. doi: 10.33317/ssurj.410

23. Zhu, H., Lu, Z., He, J., & Zhu, Y. (2024). Automotive fire alarm system based on multi-sensor fusion. *Fourth International Conference on Sensors and Information Technology (ICSI 2024)*, 89. doi: 10.1117/12.3029223

24. Bany Salameh, H. A., Dhainat, M. F., & Benkhelifa, E. (2021). An End-to-End Early Warning System Based on Wireless Sensor Network for Gas Leakage Detection in Industrial Facilities. *IEEE Systems Journal, 15*(4), 5135–5143. doi: 10.1109/jsyst.2020.3015710

25. Manoj, S., & Valliyammai, C. (2023). Drone network for early warning of forest fire and dynamic fire quenching plan generation. *EURASIP Journal on Wireless Communications and Networking, 2023*(1). doi: 10.1186/s13638-023-02320-w

26. Davis, M., & Shekaramiz, M. (2023). Desert/Forest Fire Detection Using Machine/Deep Learning Techniques. *Fire, 6*(11), 418. doi: 10.3390/fire6110418

27. Chuka Anthony Arinze, Izionworu, Vincent Onuegbu, Daniel Isong, Cosmas Dominic Daudu, & Adedayo Adefemi. (2024). Integrating artificial intelligence into engineering processes for improved efficiency and safety in oil and gas operations. *Open Access Research Journal of Engineering and Technology, 6*(1), 039–051. doi: 10.53022/oarjet.2024.6.1.0012

28. Bellas, R., Gómez, M. A., González-Gil, A., Porteiro, J., & Míguez, J. L. (2019). Assessment of the Fire Dynamics Simulator for Modeling Fire Suppression in Engine Rooms of Ships with Low-Pressure Water Mist. *Fire Technology, 56*(3), 1315–1352. doi: 10.1007/s10694-019-00931-8

29. Fan, C., Bu, R., Xie, X., & Zhou, Y. (2021). Full-scale experimental study on water mist fire suppression in a railway tunnel rescue station: Temperature distribution characteristics. *Process Safety and Environmental Protection, 146*, 396–411. doi: 10.1016/j.psep.2020.09.019

30. Liu, Y.-C., Jiang, J.-C., & Huang, A.-C. (2022). Experimental study on extinguishing oil fire by water mist with polymer composite additives. *Journal of Thermal Analysis and Calorimetry, 148*(11), 4811–4822. doi: 10.1007/s10973-022-11645-5

31. Farrell, K., Hassan, M. K., Hossain, M. D., Ahmed, B., Rahnamayiezekavat, P., Douglas, G., & Saha, S. (2023). Water Mist Fire Suppression Systems for Building and Industrial Applications: Issues and Challenges. *Fire, 6*(2), 40. doi: 10.3390/fire6020040

32. Peshoria, S., Nandini, D., Tanwar, R. K., & Narang, R. (2020). Short-chain and long-chain fluorosurfactants in firefighting foam: a review. *Environmental Chemistry Letters, 18*(4), 1277–1300. doi: 10.1007/s10311-020-01015-8

33. Mazumder, N.-U.-S., Hossain, M. T., Jahura, F. T., Girase, A., Hall, A. S., Lu, J., & Ormond, R. B. (2023). Firefighters' exposure to per-and polyfluoroalkyl substances (PFAS) as an occupational hazard: A review. *Frontiers in Materials*, 10. doi: 10.3389/fmats.2023.1143411

34. Zhao, J., Yang, J., Hu, Z., Kang, R., & Zhang, J. (2024). Development of an environmentally friendly gel foam and assessment of its thermal stability and fire suppression properties in liquid pool fires. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 692*, 133990. doi: 10.1016/j.colsurfa.2024.133990

35. Rohilla, M., Saxena, A., Tyagi, Y. K., Singh, I., Tanwar, R. K., & Narang, R. (2021). Condensed Aerosol Based Fire Extinguishing System Covering Versatile Applications: A Review. *Fire Technology, 58*(1), 327–351. doi: 10.1007/s10694-021-01148-4

36. Kim, Y.-H., Lee, M., Hwang, I.-J., & Kim, Y.-J. (2019). Noise Reduction of an Extinguishing Nozzle Using the Response Surface Method. *Energies, 12*(22), 4346. doi: 10.3390/en12224346

37. Ghorbani, H., Abdali, M. R., Mohamadian, N., & Wood, D. A. (2021). Petroleum Well Blowouts as a Threat to Drilling Operation and Wellbore Sustainability: Causes, Prevention, Safety and Emergency Response. *Journal of Construction Materials*. doi: 10.36756/jcm.si1.1

38. Negi, P., Pathani, A., Bhatt, B. C., Swami, S., Singh, R., Gehlot, A., Thakur, A. K., Gupta, L. R., Priyadarshi, N., Twala, B., & Sikarwar, V. S. (2024). Integration of Industry 4.0 Technologies in Fire and Safety Management. *Fire, 7*(10), 335. doi: 10.3390/fire7100335

39. Titu, M. F. S., Pavel, M. A., Michael, G. K. O., Babar, H., Aman, U., & Khan, R. (2024). Real-Time Fire Detection: Integrating Lightweight Deep Learning Models on Drones with Edge Computing. *Drones, 8*(9), 483. doi: 10.3390/drones8090483