British Journal of Environmental Studies
ISSN: 2755-0982
DOI: 10.32996/bjes
Journal Homepage: www.al-kindipublisher.com/index.php/bjes

BJES
AL-KINDI CENTER FOR RESEARCH AND DEVELOPMENT

| RESEARCH ARTICLE

Cutting-Edge Developments in Fire Dynamics: Implications for Thermal Injuries and Medical Response

Amit Kumar Dhali[1], Antu Roy[2], and Shubhashish Dash[3]✉
[1]*Department of Computer Science and Engineering, Comilla University, Cumilla-3506, Bangladesh*
[2]*Independent Researcher, Khulna, Bangladesh*
[3]*FLEX LTD., Milpitas, CA 95035, USA*
Corresponding Author: Shubhashish Dash, **E-mail**: sdash246@gmail.com

| ABSTRACT
The study of fire dynamics is largely concerned with gaining an understanding of the factors that control the transport of heat and the propagation of flames. It is vital to have a comprehensive understanding of these systems in order to accurately forecast the behavior of fires and to devise ways that are efficient in suppressing them. Numerous developments in computational modeling, materials science, and sensor technology have been the driving forces behind the substantial progress that has been made in the field of fire research in recent years. This study investigates the fundamental principles of heat transport, including conduction, convection, and radiation, as well as the roles that these ideas play in the propagation of flames in a variety of situations and orientations. An investigation on the movement of thermal energy between a number of different locations is carried out. The dynamics of flame propagation, which include patterns that are turbulent, vertical, and horizontal, are still being investigated in a continuous manner. Furthermore, hardly no research has been done to investigate how these systems influence the spread of flames and the harm caused by heat. Considerable attention is placed on the integration of contemporary technology, spanning computational fluid dynamics (CFD), artificial intelligence (AI), sophisticated fire-resistant materials, and automated suppression systems, among others. As a result of these advancements, fire risk assessment, early detection, and emergency medical response have all seen significant improvements, particularly in potentially dangerous scenarios. The research demonstrates the challenges that are experienced when attempting to accurately predict the conduct of fires in real-world circumstances for example. These problems are the result of the complex interaction between the materials, ventilation, and environmental elements that are available in the surrounding area. In addition to this, it investigates the ways in which a better understanding of fire dynamics could allow breakthroughs in burn management, structural safety, and medical preparation. Following the conclusion of the study, an outline of potential research objectives that will be carried out is presented. Through the utilization of interdisciplinary collaboration, the improvement of fire models, and the development of more advanced firefighting equipment, the purpose of these strategies is to improve the health outcomes that are associated with fires.

| KEYWORDS
Fire Dynamics, Heat Transfer, Flame Spread, Thermal Propagation

| ARTICLE INFORMATION
ACCEPTED: 12 May 2025 **PUBLISHED:** 07 June 2025 **DOI:** 10.32996/bjes.2025.5.1.1

1.0 Introduction
Modern engineering and safety planning require increasingly important fire dynamics research. As urban infrastructures become increasingly complex and as wildfire occurrences increase, it is necessary to understand how heat transfers and how flames spread for building design purposes to reduce risk of losses due to fires and to improve firefighting technique (Negi et al., 2024; Hossain, 2021, 2022; Hossain et al., 2023). Improved computational simulations and experimental fire testing have enhanced new insights

into fire behavior, and made significant contributions to fire risk mitigation and improvement of fire prevention strategies. This review analyses these developments in order to point out important progress in the field and its relevance to fire safety engineering (Hossain & Alasa, 2024; Hossain et al., 2024). It is generally acknowledged that fire is one of the most damaging natural and anthropogenic hazards. It is responsible for a considerable number of deaths of people, extensive damage to property, environmental degradation, and disruptions to economic activity all over the world. Drysdale (2011) asserts that the catastrophic effects of fire highlight the importance of having a comprehensive understanding of fire dynamics. This field of study comprises the mechanisms that are responsible for the ignition, spread, and development of fires throughout time. For the purpose of strengthening fire safety, informing the design of fire-resistant materials, and improving fire detection, suppression, and control tactics, it is essential to have a comprehensive understanding of fire dynamics (Hossain & Alasa, 2024a,b). The fact that research in this area encompasses a variety of fields, including as architecture, materials science, fire safety engineering, and emergency response planning, is evidence of the field's transdisciplinary significance and application. The process of heat transfer is one of the fundamental aspects of fire dynamics, and it plays an extremely important role. There are three basic mechanisms that are responsible for heat transfer, which are conduction, convection, and radiation (Shi, 2025; Negi et al., 2024). Heat transfer is the physical process that drives the formation and propagation of fire. The term "conduction" refers to the process of transferring thermal energy by means of direct contact with solid materials. This process can undermine the structural stability of a building by weakening the components that bear the load. The process of convection involves the transfer of heat through gases or liquids. This process is especially important in the propagation of smoke and fire in situations that are either vented or partially enclosed. Radiation, on the other hand, is a dominant role in the rapid escalation of fires over wide regions or between structures that are closely positioned (Alasa et al., 2025; Hossain et al., 2024). Radiation is a phenomenon that enables heat to travel through electromagnetic waves. Having a comprehensive understanding of these mechanisms is essential for accurately anticipating the behavior of fires, optimizing the design of buildings, and developing strategies that are effective in putting out fires. Another basic feature of fire dynamic is the propagation of flames, which is in addition to the transfer of heat. There are a number of factors that might influence flame spread, including the physical and chemical qualities of the fuel, the ambient climatic conditions, the surface orientation, and the existence of external heat sources (Zhang, 2025). Flame spread determines how quickly and extensively a fire can expand. There are a few different kinds of flame spread that have been identified in the research. Surface flame spread is the propagation of flames along the surface of combustible substances including wood, textiles, and synthetic polymers. This kind of flame spread is referred to as surface flame spread. The occurrence of this is a common occurrence in both residential and industrial fire settings. It is common for upward and cavity flame spread to take place in architectural cavities or vertical spaces (Drysdale, 2011; Hossain et al., 2024a,b).

In these environments, flame propagation is expedited by amplified heat feedback, which frequently results in deadly fires in high-rise buildings. In addition, the behavior of flame spread can be categorized as either laminar or turbulent upon the basis of the dynamics of the airflow. When compared to turbulent flame spread, which is driven by chaotic air movement and ventilation patterns, laminar flame spread happens in surroundings that are steady and low-velocity. This makes turbulent flame spread more unpredictable and dangerous. In order to create realistic fire models, improve material testing standards, and strengthen fire laws and regulations, it is vital to have a solid understanding of the mechanisms that cause fires to spread. The correlation between heat transfer and flame propagation is the foundation of contemporary research on fire dynamics. This relationship has significant consequences for the prevention of loss of life, the reduction of structure damage, and the improvement of overall fire resilience in both urban and rural environments.

2.0 Recent Advances in Fire Dynamics Research

Our ability to predict and to control fire will have been significantly improved by technological advancements. In parallel, modern Computational Fluid Dynamics (CFD) models, AI driven fire prediction systems, experimental techniques, and advanced fire testing have increased our understanding of fire behavior (Johansson & Svensson, 2019). In addition, the development of fire-resistant coatings, smart materials as well as automated suppression systems has further improved fire mitigation strategies. The graphic depicts the three-phase mechanism of flame spread in a turbulent reactive flow. It provides a detailed explanation of how flame kernels develop and interact with vertical structures as the fire spreads. The first stage, which is referred to as "Phase 1," is characterized by the formation of rolling flame kernels and small eddies that do not react at the flame front (Johansson & Svensson, 2019; Zhang, 2025). Flame kernels start to appear and spread along the surface, which leads to the development of a rudimentary flame structure. Localized ignition points are responsible for the generation of these kernels, which are impacted by turbulence on a smaller scale. The second phase is characterized by a transitional stage that includes both extinction and reignition. As the vortices reattach themselves to the surface, they disintegrate and cause disruption to the structure of the flame, which ultimately results in the temporary extinguishment of the flame. Reinvention, on the other hand, takes place very quickly and is maintained by the primordial flame. This phase is essential for opposing flame spread, which occurs when the flame front moves in the opposite direction of the flow that is flowing in (Chen et al., 2023). Heat feedback and flame kernel regeneration lend a hand in this process. The entrainment of flame kernels by coherent vortices in a reactive flow regime is demonstrated in the third phase of the experiment. The flame dynamics are dominated by large vortices, which are responsible for moving flame kernels downstream. As the flame continues to stabilize, it transforms into a sustained diffusion flame, which is supported by a fuel-rich zone and intensified by turbulent mixing. Strong aerodynamic and thermal interactions are the driving forces behind this last phase, which reflects the fully developed spread of the fire. For the purpose of comprehending the propagation of turbulent flames and developing efficient techniques for fire suppression, this tiered model is absolutely necessary. In this review, fire dynamics are reviewed from heat transfer mechanisms and flame spread phenomena standpoint (Liang, 2025). It investigates the principles, the research developments, and the technologies of current times concerned with fire prevention and control. The second part of the review touches upon the practical applications in fire safety engineering, and provides future directions in terms of improvement of the fire-resistant materials, predictive modeling techniques and firefighting technologies.

3.0 Fundamentals of Fire Dynamics

Fire dynamics is the science of how fires ignite, spread and develop depending on the environment. It thus deals with the interaction between heat, fuel, oxygen and chemical reaction giving rise to combustion. Predicting fire behavior, constructing better fire safety measures and developing efficient suppression systems are important based on the principles of fire dynamics with their phases (Figure 1). This section describes the basic fundamentals of fire dynamics (i.e., the fire triangle, combustion theory, and key factors affecting a fire behave) (Chen et al., 2023).

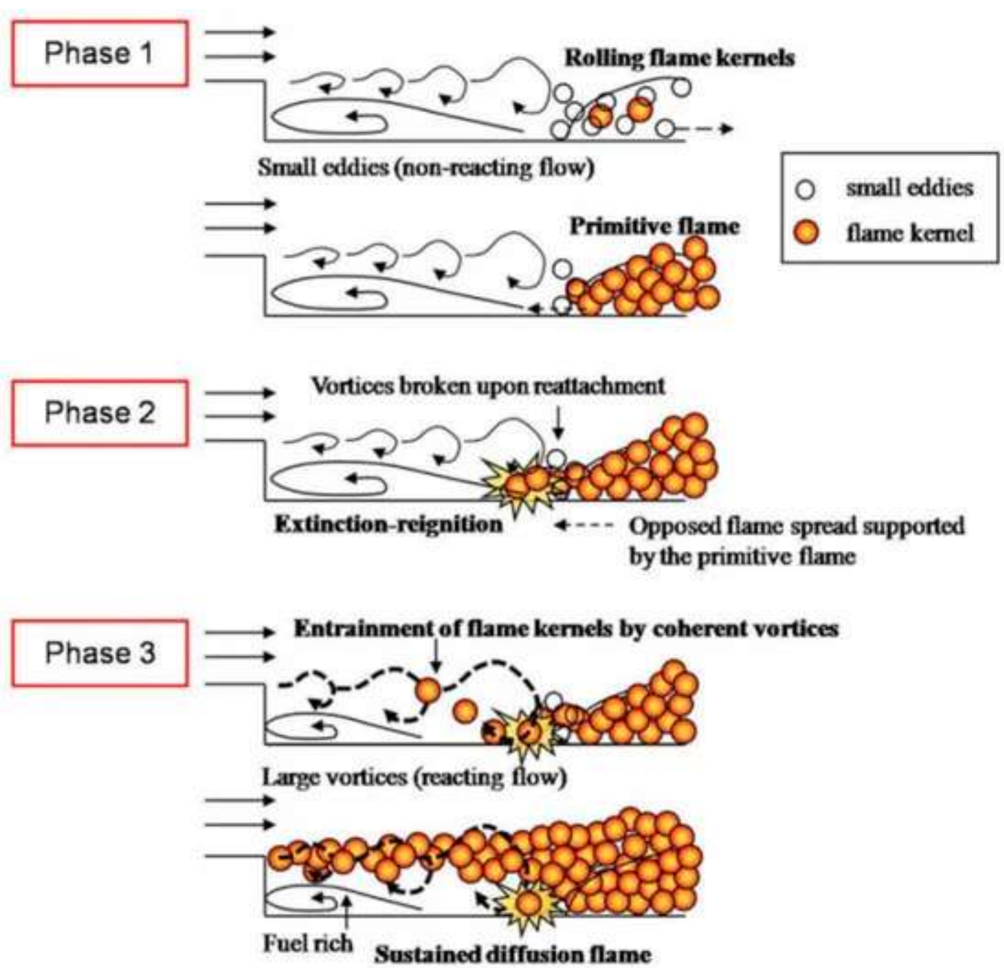

Figure 1. Three phases of the transient flame spread. Adapted from "A Review of Combustion and Flame Spread over Thermoplastic Materials - Research Advances and Prospects (Adopted from Yanqiu Chen, 2023).

3.1 The Fire Triangle, Tetrahedron and Development

A fundamental understanding of the components that keep a fire running is required in order to effectively prevent and put out fires. This information is essential in order to efficiently put out fires. Heat, fuel, and oxygen are the three essential elements that comprise the fire triangle. The fire triangle is a three-dimensional structure. It has been stated by Araújo (2025) that heat is the primary source of energy that is necessary for the initiation of combustion. On the other hand, the term "fuel" can be used to refer to any flammable substance that is having the ability to sustain burning. In addition to this, oxygen is a catalyst for the chemical reactions that are essential for the spread of fire. To further elaborate on this idea, the fire tetrahedron contains a fourth component that is referred to as chemical chain reactions. The continuous exothermic activities that generate additional heat in order to keep combustion going are the focus of this component, which lays an emphasis on those processes. In this concept, it is emphasized that putting out a fire can be performed by putting out any one of the following three elements: cooling (which includes removing heat), starving (which requires removing fuel), or smothering (which involves eliminating oxygen) (Hossain, 2022). In addition, flames progress through a number of distinct stages, each of which is marked by a distinct collection of behaviors and threats unique to that stage. The initial phase of ignition, which is often referred to as the "enlightenment" phase, starts when a fuel source is exposed to an enough amount of heat in the presence of oxygen. Sparks, open flames, or electrical faults are the most common causes of this phase, according to Pyne (2022). Following the lighting of the fire, the growth phase of the fire is driven by heat transmission processes such as conduction, convection, and radiation. These mechanisms spread the fire to combustible objects that are located in the surrounding area. After that, the fire reaches its "peak intensity," which is the point at which it consumes all of the oxygen and fuel that is available to it. The last phase, which is referred to as the extinction phase, is the period in which the fire is put out as a result of the exhaustion of fuel or the successful use of firefighting remedies. Having a firm understanding of these stages is extremely required in order to construct effective fire suppression systems and maintain compliance with safety requirements.

3.2 Heat Release Rate (HRR) and Fire Intensity

The Heat Release Rate (HRR) is a measurement that determines the amount of energy that is produced by a fire over a period of time. It is stated in either kilowatts or megawatts (Hopkin, 2025). Understanding fire dynamics requires conducting an analysis of the HRR. A high HRR indicates that the fire, which is affected by the type of fuel, ventilation, and surface area, is more intense. This is because the HRR is a measure of the intensity of the fire. The behavior of fires is also influenced by environmental factors, such as the configuration of the fuel, the availability of oxygen, and the weather conditions, which include wind and humidity (Shabanlou et al., 2025). The combustion process results in the production of fire plumes, which are hot gases that rise to the surface due to their buoyancy. The movement of smoke and the distribution of hazardous gases like carbon monoxide and carbon dioxide can both be affected by these plumes, according to Sun (2025). In addition to the planning of evacuations and the implementation of effective measures for fire control, these components are vital when it comes to calculating the progression of a fire.

4.0 Heat Transfer Mechanisms in Fire Dynamics

Fire dynamics is based on heat transfer and in turn, plays a major role in the spread and the intensity of the fire. It determines the rate of propagation of fire through the materials and how effectively it can be controlled (Lei, 2025). Conduction, convection and radiation are the three major mechanisms of heat transfer in fire dynamics. Accurate knowledge of these mechanisms is essential to designing fire resistant materials, developing better and more efficient rules for firefighting, and designing and improving fire protection systems.

4.1 Conduction - Heat Transfer Through Solids

The second way heat is transferred without the movement of material is conduction which is a process in which heat energy is transferred through a solid material. In fact, this mechanism is crucial to structural fire spread through walls, floors and ceilings, where heat may go, igniting materials in adjacent spaces (Hossain, 2022; Zhang et al., 2024). The ability of a material to transfer heat is defined as the thermal conductivity. For example, metals have high conductivity and good ability to spread heat, while wood and insulation are materials with low conductivity and serve as fire barriers. Gypsum board and concrete are fire resistant materials that are designed to limit conduction and slow down fire spread in buildings (Shabanlou et al., 2025). Conduction is influenced by temperature gradients, which is the process of heat movement from higher temperature or hot regions into low temperature, or colder areas, with the risk of hidden fire propagation increased.

4.2 Convection - Heat Transfer through Fluids and Air

The transfer of heat through the transfer of gases or liquids is convection. It contributes to the upward movement of hot air and smoke and is therefore very important for the spread of flames in the occupied space.

- **Natural Convection -** Hot gases rise due to buoyancy, creating vertical fire spread in buildings, such as through stairwells and ventilation shafts.
- **Forced Convection -** External forces, such as wind or ventilation systems, can accelerate fire spread by distributing heat and smoke throughout a structure.
- **Flashover Phenomenon -** In confined spaces, convective heat buildup can lead to flashover a sudden transition where all combustible materials ignite simultaneously, making fire control extremely difficult.

4.3 Radiation - Heat Transfer through Electromagnetic Waves

The radiation is the heat energy transfer by electromagnetic waves such as infrared radiation through the absence of a medium. It is of importance in large scale fires and open environments where the radiant heat can ignite an object at a distance (Khedher, 2024). Radiant heat flux increases with temperature, allowing fire to spread across gaps between structures, vehicles, or vegetation in wildfires. Reflective surfaces can amplify or reduce radiation effects. Shiny materials like aluminum can reflect heat, while dark, rough surfaces absorb it more efficiently. In the real fire world, it is common that conduction, convection will act together or radiation will act simultaneously, and the fire spread becomes complex and difficult to predict (Parmar, 2024). In a house fire, conduction heats structural materials, convection distributes heat and smoke through air movement, and radiation preheats nearby objects, accelerating flame spread. In a wildfire, radiant heat ignites vegetation ahead of the flames, convection-driven winds intensify fire movement, and conduction spreads heat through tree trunks and branches. Several advancements in fire safety engineering have been made based on understanding of heat transfer mechanisms including (Liu, 2025).

5.0 Flame Spread Mechanisms in Fire Dynamics

Flame spread is a major factor of critical importance in fire growth and intensity and its effect determines how quickly and broadly a fire spreads across different surfaces and materials (Zhang, 2025). The flame spread mechanism is dictated by the characteristics of the fuel, environment, and the heat transfer interactions. This understanding is important to the development of fire prevention, suppression and containment strategies. Depending on the orientation of the burning surface and the conditions of the airflow in the surrounding area, there is a large degree of variation in the behavior of flame spread. This variation may be seen in the behavior of flame spread (Figure 2). Due to the fact that the two components interact with one another, this is the result (Chen et al., 2023, 2024). There are three fundamental variants that are typically differentiated from one another during the process of flame spread development. These variations include the upward flame spread, the horizontal flame spread, and the downward flame spread. The upward flame spread that takes place across vertical surfaces like walls, draperies, or building facades is mostly caused by buoyant forces. This is the case because buoyant forces are responsible for the upward flame spread. Warming materials that are positioned above the flame is caused by these forces, which cause hot gasses to rise with them. A phrase that is sometimes used to describe this phenomenon is "upward flame spread." This is one of the terms that is sometimes used. According to Ma (2025), this particular sort of spread poses a particularly serious risk in high-rise buildings due to the acceleration with which it spreads from one floor to the next. This is because of the quickness with which it spreads (Figure 2). Examples of areas where horizontal flame propagation can take place include floors, tables, and fuel beds. It is also possible for flames to spread horizontally across surfaces. Because convective heating is less successful at preheating unburned fuel in forward proximity to the flame front, this type of flame spread is often slower than vertical flame spread (Chen et al. 2024). This is not to say that vertical flame spread is not effective. Specifically, this is due to the fact that the same phenomenon is responsible for both types of flame spread. Additionally, the behavior of the material is influenced by the surface roughness, the fuel load, and the flame-retardant treatments. These two factors are also responsible for the behavior of the substance. The final type of flame spread is the downward flame spread, which occurs on things that are suspended or overhanging, such as trees or fabrics that are hanging. This type of flame spread is the most common type of flame spread. Due to the fact that it works against the natural buoyancy of hot gasses, this mode is typically the one that flows at the slowest pace. The reason for this is that you need to use more energy to move. The fact that burning objects have the potential to fall and ignite lower layers of vegetation, which adds to the spread of the fire at the level of the forest floor, can, nevertheless, be of essential relevance in the event of wildfires (Ma, 2025). This is because burning things have the potential to fall and ignite lower layers of vegetation.

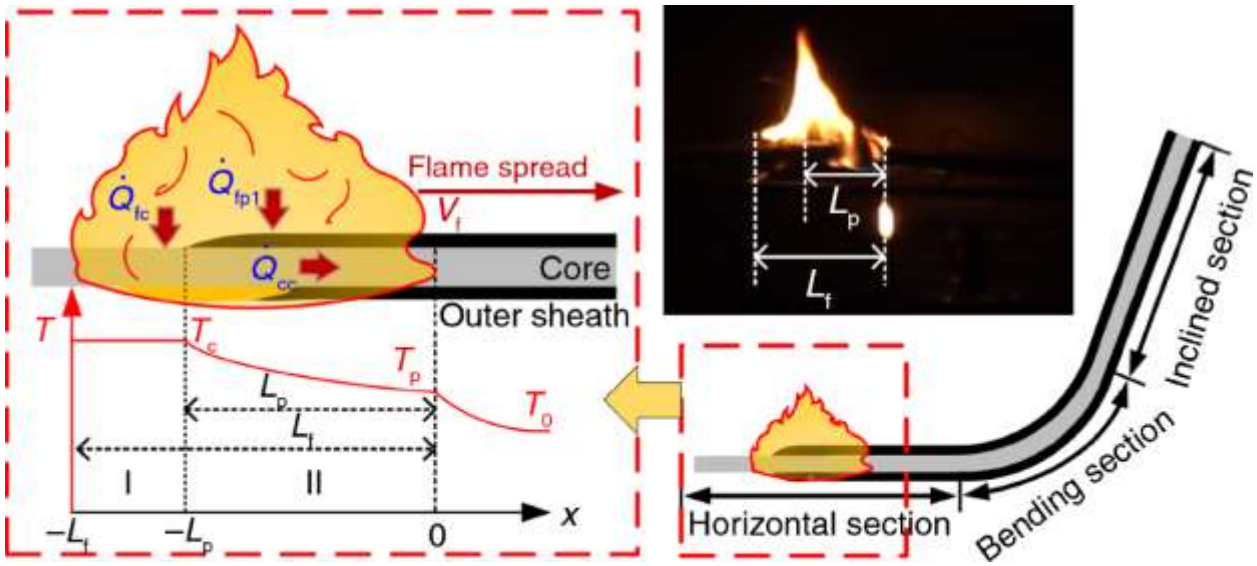

Figure 2. Types of Flame Spread Adapted by "Experimental study on the flame spread behavior and heat transfer model of upward-bending cable" by Changkun Chen, 2024.

5.1 Factors Influencing Flame Spread

Several elements are critical in ascertaining the pace and direction of flame growth. This context considers the fuel characteristics, surface orientation, environmental conditions, and oxygen availability. Materials with high flammability and low pyrolysis temperatures are more prone to ignition than other materials. Conversely, paper and textiles exemplify porous and fibrous materials that combust more rapidly than other material types due to their greater surface area. The type of fuel utilized and its inherent features are critically significant elements in this context. The presence of moisture will delay the igniting process by absorbing heat. Deng (2025) contends that enclosed spaces exhibit a heightened capacity to store heat and smoke, hence accelerating the propagation of fires. Conversely, sloping or vertical surfaces facilitate heat transfer via convection and radiation, hence accelerating the dispersion of heat. In the context of surface geometry and orientation, there are several critically significant factors that must be considered. Environmental conditions, including wind, temperature, and humidity, can significantly affect flame behavior. The surrounding environment can also influence flame behavior. Higher temperatures reduce the time required for a fire to ignite compared to lower temperatures. Conversely, wind induces a tilt in the flames and enhances their upward movement, particularly in the context of wildfires. Conversely, elevated humidity levels impede or completely halt the combustion process. Consequently, the presence of oxygen and ventilation are critical factors that significantly influence the severity of a fire and its potential for expansion. The availability of oxygen and ventilation is a crucial aspect. Fires can propagate more rapidly in open areas with sufficient ventilation, while enclosed spaces with inadequate ventilation may create fuel-rich conditions that can result in backdrafts or flashovers, which are swift and violent re-ignitions that pose considerable threats to life and property (Li, 2024).

5.2 Engineering Applications and Fire Safety Measures

Our ability to control the spread of flames has significantly improved as a result of breakthroughs in fire science. This progress has been brought about by a major improvement. These advancements include the development of fire-resistant materials as well as sophisticated suppression devices. It is now possible to accomplish this goal as a result of the development of materials that are resistant to fire. Some of the most notable applications of fire-retardant materials include fire-resistant architectural designs, which make use of compartmentalization and insulation to contain fires within limited zones (Luo, 2024). Fire-retardant coatings, which delay ignition and slow flame propagation, ventilation systems, which regulate heat and smoke movement to prevent rapid fire escalation, and ventilation systems. The following list provides specific examples of a handful of these applications. When it comes to the other hand, there is still a significant obstacle to precisely forecast the development of fires in circumstances that take place in the reality world. According to Bjelland (2013), it is difficult to accurately predict the behavior of fires due to the complex interaction of heat transmission systems. This is because each system has its own unique characteristics. Radiation, conduction, and convection are all processes that fall under this category. Furthermore, there is a substantial degree of fluctuation that may be attributed to the qualities of the fuel as well as the conditions of the environment. Furthermore, the existing fire modeling systems frequently struggle to capture the entire dynamic character of flame propagation, which inhibits their capacity to create reliable projections regarding the future. This is a significant limitation of the systems. The systems have this constraint as a limitation. In the future, there is a great amount of promise that may be found in developing technologies like as machine learning, artificial intelligence, and computational fluid dynamics (CFD). These technologies have the potential to bring about enormous opportunities. In the future, research will be carried out with the purpose of achieving the following objectives: the development of more accurate prediction models; the enhancement of fire-resistant materials that are specifically built for buildings and transportation; and the advancement of automated suppression systems that are able to respond in real time. The implementation of these technologies will not only enhance fire safety, but they will also contribute to the protection of vital infrastructure and the preservation of life. In addition to that, they will improve the safety of fires.

6.0 Recent Advancements in Fire Dynamics Research

In recent years particularly, technological innovations and the interdisciplinarity have made fire dynamics research considerably progress. With these advancements, our understanding of the fire behavior has improved, and these advancements have led to more effective strategies for prevention, suppression and risk assessment of fires (Chen, 2021). Exploration of new fire-resistant materials, latest fire dynamics experimental fire testing, computational fire dynamics research, new firefighting technologies etc.

6.1 Computational Fire Modeling and Simulations

The application of computer models has resulted in a revolution in the field of fire research. This change has been brought about by the fact that it is now feasible to properly mimic the behavior of fires in environments that present intricate operational requirements. The utilization of computer models has been the driving force behind this change. They are able to generate predictions regarding the growth of fires, the transmission of heat, and the displacement of smoke in real-world settings, which is a significant contribution to the field of fire research, according to McGrattan (2012). This is a substantial contribution to the field of fire research. One of the devices that is utilized the most commonly is the Fire Dynamics Simulator (FDS), which was constructed by the National Institute of Standards and Technology (NIST), which is the agency that is responsible for its design. When combined with computational fluid dynamics (CFD) models, finite difference simulations (FDS) make it feasible to conduct in-depth simulations of the spread of fire, the movement of smoke, and the thermal interactions that take place within structures and open spaces. These simulations can be carried out in order to better understand the dynamics of these phenomena. In applications such as building safety design, wildfire prediction, and industrial fire risk assessment, computational fluid dynamics (CFD) techniques are essential. This is due to the fact that these approaches reflect airflow, turbulence, and combustion processes. Several instances of situations in which computational fluid dynamics (CFD) techniques are applied are presented below. In addition, it is important to take into consideration the fact that Artificial Intelligence (AI) and Machine Learning (ML) are becoming an increasingly important component in the process of fire prediction. As a result of the utilization of models that are driven by artificial intelligence, it is possible to make advancements in the areas of early fire detection, real-time risk forecasting, and strategic firefighting response (Hossain et al., 2025; Goffer et al., 2025; Islam et al., 2025; Hossin et al., 2025). By utilizing machine learning techniques, it is possible to perform the processing of big datasets, which may include previous fire events, environmental variables, and sensor inputs. This can be accomplished. Once these algorithms have been developed, they can be applied to recognize patterns and forecast the behavior of fire dissemination (Hossain et al., 2023). An additional use of artificial intelligence that is currently being investigated is the construction of robots that are capable of combating fires on their own. The purpose of these robots is to do tasks in potentially dangerous environments where the amount of human involvement involved is restricted. Individually and collectively, each of these technologies is a symbol of the future of intelligent and predictive fire management systems. This is true for both the aforementioned technologies (Manik, 2022, 2023, 2025; Manik et al., 2021, 2022; Hassan et al., 2022).

6.2 Development of Fire-Resistant Materials

Fire-resistant materials are crucial for improving safety in buildings, transit networks, and industrial environments. Contemporary research emphasizes the creation of materials capable of enduring severe temperatures and efficiently inhibiting flame growth (Soares, 2024). Nanotechnology-derived fire retardants, including nanocomposites, represent a notable advance that enhances fire resistance in polymers, textiles, and coatings. Materials containing graphene exhibit remarkable thermal stability and low flammability, rendering them suitable for sophisticated fireproofing applications. Moreover, the advent of intelligent fire-resistant materials has led to innovations including self-repairing coatings that autonomously mend heat-induced damage, and phase-change materials (PCMs) that absorb and store thermal energy, thus alleviating temperature increases within edifices. Fire suppression systems have progressed via the adoption of more effective extinguishing agents and sophisticated firefighting technologies. Water mist and hybrid suppression systems represent significant developments. These devices generate fine water droplets that effectively absorb heat and displace oxygen, rendering them suitable for sensitive areas like data centers and industrial facilities (Dabous, 2024). Moreover, hybrid gas-water systems augment firefighting efficacy by integrating the cooling attributes of water with the inverting characteristics of gas. Simultaneously, firefighting drones and robotics are revolutionizing emergency response. Drones equipped with thermal imaging cameras provide instant situational awareness in perilous or unreachable locations, while autonomous firefighting robots are being developed for extreme environments, such as chemical fires or space missions, where human involvement is perilous or unfeasible. These inventions are revolutionizing the future of fire management and safety (Barikdar et al., 2022; Khair et al., 2024; Rahman et al., 2024).

6.3 Advances in Wildfire Prediction and Management

The increasing frequency and intensity of wildfires due to climate change necessitates the adoption of advanced technologies for forecasting, monitoring, and control (Srivastava, 2025). Satellite and AI-driven detection technologies are spearheading this change. NASA's Fire Information for Resource Management System (FIRMS) offers real-time satellite imagery for the global monitoring of current fires. Simultaneously, AI-driven early warning models evaluate factors such as climate trends, wind direction, and fuel moisture to accurately forecast wildfire risks and potential spread. These predictive tools enable the swift allocation of firefighting resources and evacuation plans (Alam et al., 2025; Manik et al., 2025a,b; Mahmud et al., 2025; Haldar et al., 2025; Manik, 2021). Concurrently, improvements in aircraft firefighting are revolutionizing the suppression of large-scale wildfires. Autonomous firefighting aircraft are being developed and evaluated to operate in extreme conditions without endangering human pilots. Drones equipped with chemical fire-retardants are utilized to distribute fire-suppressing agents to inaccessible or perilous woodland regions. These unmanned systems can operate continually, improving coverage and efficiency in wildfire management (Rahman et al., 2024; Khan et al., 2024; Das et al., 2025). These inventions are crucial for protecting ecosystems, assets, and human lives under increasing wildfire threats.

7.0 Advancements, Challenges, and Future Perspectives

Research in fire dynamics has allowed us to greatly understand heat transfer, flame spread and fire behavior in different environments. Improved safety measures and regulations are the fruits of the integration of computational modeling, fire resistant materials and improved suppression techniques. Yet, although progress has been made in predicting complex fire scenarios, enforcing global fire safety standards and handling novel threats like climate aided wildfire and industrial fire risks, much yet remains to be done (Zang, 2023). However, with evolution in fire science continuing, further research and technological innovations are still needed to further improve fire safety and the strategies to handle fire.

7.1 Challenges in Fire Dynamics Research

Despite the progress yet made, fire dynamics research has yet many challenges to overcome limiting its full extent. The prediction of fire spread is in fact one of the major challenges. Multiple factors such as fuel composition, environment, and structural configurations influence fire behavior, which makes a precise modeling hard (Figure 3). Meanwhile, the real use of AI and IoT-based fire detection and suppression systems is in a very early stage and still has to be worked out as well as legally approved (Carta, 2023). The bigger challenge is the enforcement of global fire safety standards. Fire codes and regulations can vary widely from region to region, and many developing countries have a mismatch between codes and regulations and actual practice, which is increasing the fire risk. Furthermore, although there are still not widely applied, sustainable and cost-effective fire-resistant materials are not accessible due to high production costs. Wildfires have become more frequent and dangerous with climate change and do not lend themselves to reduction through standard fire management strategies. These challenges require interdisciplinary collaboration with reform of policies and development of new technologies in an ongoing effort. Fire safety regulations emphasize proactive risk assessment and fire prevention strategies to reduce the likelihood of fire incidents (Xin & Huang, 2013; Danzi, 2021).

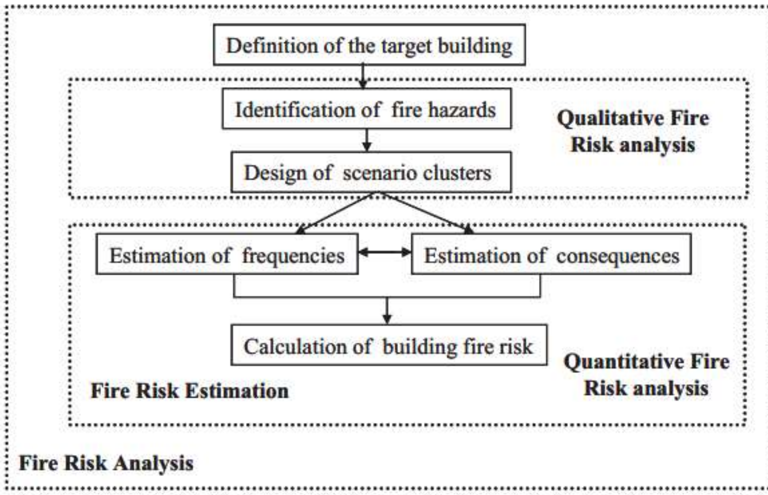

Figure 3. Flow chart of fire risk analysis of buildings. Adapted by Fire risk analysis of residential buildings based on scenario clusters and its application in fire risk management (Adopted from Xin & Huang, 2013).

7.2 Research Gaps in Fire Dynamics

In addition, there are several research gaps that remain to be resolved to gain further improvement in fire safety. While the current fire spread models are advanced, they are yet to fully replicate real world fire behavior in areas such as high-rise buildings, industrial area, and densely forested areas. To construct more comprehensive predictive models that include additional variables including wind patterns, fuel distribution, and thermal interactions further research is necessary (Zhijie, 2024). Finally, the development of next generation of the fire suppression agents is still under the research study. Standard fire suppressants are good, but either new fire suppressants are needed with less long term ecological and health impact, or we need a formulation of active agents that use the existing fire suppressant, that minimizes long term environmental and health implication (Hossain, 2021, 2022). Secondly, the key research gap is regarding human behavior during fire emergencies. With better insight into how people behave in different fire situations, evacuation strategies and fire safety training can be significantly improved. Also, the effects of long-term techniques of fire suppression such as chemical based agents need to be studied further to understand their impacts on the environment and human health. Another emerging area of research around developing fire resistant materials for future infrastructure also include work on nanotechnology-based coating, self-healing materials and sustainable fireproofing solutions still in the early stages of development (Hossain et al., 2024).

7.3 Future Directions in Fire Dynamics Research

However, moving forward, given progress in fire science, several critical areas will drive future research and innovation. Big data analytics and artificial intelligence are both expected to contribute crucial abilities in real time fire prediction, fire risk assessment, and automated suppression systems (Hossain et al., 2024; Sultana et al., 2024; Manik et al., 2018). With the aid of huge repositories of historical fire incident data, environmental conditions and building vulnerability repository, machine learning algorithms can aid our fire forecasting model (Carta et al., 2023; Miah et al., 2025; Barikdar et al., 2025; Hassan et al., 2025; Moniruzzaman et al., 2025). An important focus area is the development of next generation fire resistant materials. Fire protection will see a number of new advances, including the development of a more durable and efficient fireproof structure through advances in nanotechnology, self healing coatings and smart materials. Finally, methods for sustainable firefighting are also starting to be taken into consideration the development of firefighting products and work on eco friendly fire fighting product like eco friendly fire extinguishers and other products that cause minimum harm to environment (Hossain et al., 2024). Also, international fire and fire safety Regulations and response strategies must continue to be jointly developed by global partners. As large-scale fires occur across numerous regions around the globe, the cooperation between governments, research institutions and industries will overlap to develop standard frameworks for fire safety to support the preparation and mitigation of fires across the globe (Singh et al., 2024).

7.4 Final Thoughts

Fire dynamics play an important role in developing fire safety, reducing property loss, and saving lives. Computational modeling and prediction with the help of artificial intelligence, as well as advancements in fire resistant materials, are the trend that will affect the future of fire protection. Nevertheless, future investment in fire science and policy development are needed to address existing challenges and research gaps (Yaşayan, 2023). With the use of cutting-edge technologies, the global community should improve upon enforced stronger regulations and implement proactive prevention strategies with the aim of creating a safer and more fire resilient future. As long as humans continue their environments with fire, they will be exposed to fire hazards, but with sustained research and innovation, the risks associated with them can be significantly reduced (Islam et al., 2023; Ashik et al., 2023; Khan et al., 2024). Fire incidents in the real world provide practical insights regarding fire behaviour, risk factors as well as the effectiveness of fire safety measures. Case studies allow researchers and policy makers to understand and revise fire prevention strategies and better regulate behaviour. This section focuses on major fire disasters, lessons learned and the application of fire dynamics research in real world situations (Johansson, 2019).

8.0 Heat, Injury, and Medical Preparedness

Fire dynamics, which is the study of how flames begin, spread, and grow, not only plays an important function in structural engineering and disaster prevention, but it also plays a critical role in medicine, notably in the prevention, assessment, and treatment of thermal injuries. Fire dynamics is a field of study that focuses on the study of how flames begin, spread, and develop (Figure 4). When it comes to healthcare systems and emergency medical response scenarios, having a solid understanding of the physics that underpins flame propagation and heat transmission has major implications. The reason for this is because wildfires, industrial accidents, and urban fires are becoming increasingly common as a consequence of climate change and large populations of people living in close proximity to one another (Manik, 2021, 2022, 2023, 2025; Hossain, 2021, 2022). The study of fire dynamics has recently undergone a number of breakthroughs that have shed light on the manner in which numerous factors, such as the composition of the fuel, ventilation conditions, flame spread rates, and thermal radiation, contribute to the intensity and pattern of burn injuries. For the purpose of example, modern computational models are now able to simulate the method by which heat energy is conveyed in enclosed situations through the processes of conduction, convection, and radiation. In order to offer reliable estimates of temperature exposure zones, several models are utilized (Miah et al., 2019; Hossain & Alasa, 2024a,b). Not only is this information necessary for calculating the amount of time that heat contact is exerted on human skin, but it is also necessary for determining the intensity of that contact, which in turn helps to foresee the depth and extent of burns. The findings of this research also demonstrate how rapid flashover events can occur when flames spread over vertical surfaces or in confined spaces, such as elevator shafts and stairwells. First responders and trauma units that are engaged in the process of planning for circumstances that include a significant number of casualties should take this matter into consideration (Hossain et al., 2023).

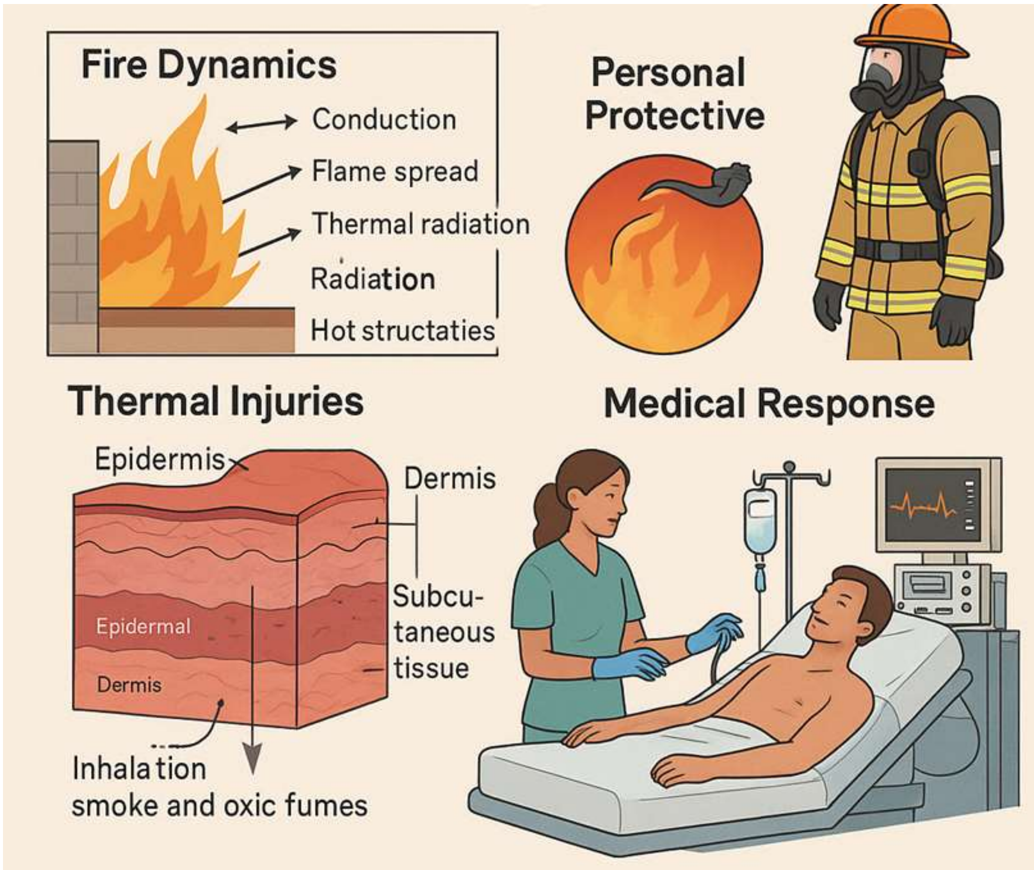

Figure 4. Interdisciplinary framework of fire dynamics, thermal injuries, and emergency medical preparedness.

Injuries that are brought on by fire typically take place in milliseconds and involve a range of complex damage pathways. These damage pathways include the loss of epidermal tissue, the inhalation of toxic fumes, and the disintegration of tissue as a result of hypothermic circumstances. When emergency physicians have access to comprehensive data from scientific investigations into fire dynamics, they are able to more precisely foresee sequelae such as airway edema, carbon monoxide poisoning, or systemic inflammatory responses (Miah et al., 2019; Manik et al., 2020a,b). This occurs because these physicians are able to better understand the dynamics of fires. In addition, these findings are of utmost significance when it comes to the creation of triage algorithms that can be utilized in emergency scenarios that involve flames. As an illustration, understanding the phases of flame kernel development and the behavior of diffusion flames can assist in determining whether a victim most likely suffered from primary burn mechanisms (also known as direct flame), secondary burn mechanisms (also known as radiant heat), or tertiary burn mechanisms (also known as structure collapse).

A further notable contribution that fire dynamics has made to the field of medicine is the enhancement of the design of personal protective equipment (PPE), which is intended to shield individuals from harm. The creation of fire-resistant clothing materials for industrial workers and firefighters has been directly influenced by research that was carried out on the ignition temperatures of various materials, flame spread rates, and thermal degradation thresholds (Alasa et al., 2025; Hossain et al., 2024). The medical team is provided with information regarding the severity of burns that are predicted to occur in the event that protective gear fails under specific fire conditions. This not only reduces the likelihood of injuries occurring, but it also gives the medical team with information (Bulbul et al., 2018; Tanvir et al., 2024). Furthermore, real-time fire modeling and sensor-integrated building systems, both of which are products of advanced fire science, are currently being merged into smart hospitals and emergency care infrastructure. Both of these technologies are products of the field of fire scientists. The emergency medical workers are provided with the necessary amount of time they require to shift patients, prioritize burn victims, and allocate intensive care resources as a result of the early alerts and precise identification of risk zones that are made possible by these technologies (Hossain et al., 2024).

In conclusion, the most recent developments in fire dynamics are not only vital for the suppression of flames and the reinforcement of structures, but they are also essential for the preparation of medical staff and the treatment of patients who have suffered trauma. Contemporary fire research helps us understand, prevent, and treat thermal injuries in a more effective manner by bridging the gap between engineering and clinical science. This is accomplished through the process of bridging the gap between engineering and clinical science. In order to minimize the burden of injuries and enhance patient outcomes in fire-related catastrophes, it will be essential for fire scientists, healthcare specialists, and emergency planners to collaborate with one another. This is due to the fact that the risks of fire in today's society continue to increase.

9.0 Conclusion

Fire dynamics has undergone significant study, depths in heat transfer, flame spread, and fire suppression techniques have all been studied. Improvements in fire safety and minimization of risk have benefited greatly from enhancements in computational modeling, AI driven fire detection, and new fire-resistant materials. However, such developments do not mean challenges such as the accurate prediction of the fire spread, the enforcement of the fire safety regulation, and the need for sustainable fire-resistant solutions are not yet solved. This calls for a multidisciplinary approach that entails scientific research, technological innovation and policy reform to come up with better fire prevention and mitigation strategies. As the technologies of both fire and firefighting become more sophisticated, and the potential for climate change and urbanization to drive increased fire threats exponentially continue to grow, so does the need for more sophisticated fire dynamics research. Going forward, future fire dynamics will be the combination of AI, IoT based fire monitoring and eco friendly fire suppression methods. Further reinforcement in fire protection strategy will be gained through materials development of next generation fire resistant materials and next generation predictive modeling techniques. At the same time, global cooperation for fire safety research and policy making will be crucial to standardizing regulations and enhancing emergency response of other countries. As the fire hazards are evolving continuously, funds should be continued in the field of research, education, and getting people aware of it. Working to address current challenges and explore new frontiers in fire science will help increase fire safety and save lives and property, and help us move to a more sustainable future.

Funding

This research received no external funding.

Acknowledgements

We would like to express our gratitude to all the co-authors for their contribution and critical reviews from the anonymous reviewers.

Conflicts of Interest

No potential conflict of interest relevant to this article was reported

References

[1] Alam, G. T., Chy M. A. R., Rozario, E., Moniruzzaman, M., Hossain, S., Uddin, M., Manik, M. M. T. G. (2025). AI-Driven Optimization of Domestic Timber Supply Chains to Enhance U.S. Economic Security. Journal of Posthumanism, 5(1), 1581–1605. https://doi.org/10.63332/joph.v4i3.2083

[2] Alasa, D.K., Hossain, D., Jiyane, G. (2025). Hydrogen Economy in GTL: Exploring the role of hydrogen-rich GTL processes in advancing a hydrogen-based economy. International Journal of Communication Networks and Information Security (IJCNIS), 17(1): 81–91. Retrieved from https://www.ijcnis.org/index.php/ijcnis/article/view/8021

[3] Araújo, C. (2025). Powers as First Causes of Generation in Plato’s Timaeus. Plato’s Power, 10, 58.

[4] Ashik, A. A. M., Rahman, M. M., Hossain, E., Rahman, M. S., Islam, S., & Khan, S. I. (2023). Transforming U.S. Healthcare Profitability through Data-Driven Decision Making: Applications, Challenges, and Future Directions. European Journal of Medical and Health Research, 1(3), 116-125. https://doi.org/10.59324/ejmhr.2023.1(3).21

[5] Barikdar, C. R., Hassan, J., Saimon, A. S. M., Alam, G. T., Rozario, E., Ahmed, M. K., & Hossain, S. (2022). Life Cycle Sustainability Assessment of Bio-Based and Recycled Materials in Eco-Construction Projects. Journal of Ecohumanism, 1(2), 151 –. https://doi.org/10.62754/joe.v1i2.6807

[6] Barikdar, C. R., Siddiqa, K. B., Miah, M. A., Sultana, S., Haldar, U., Rahman, H., … Hassan, J. (2025). MIS Frameworks for Monitoring and Enhancing U.S. Energy Infrastructure Resilience. Journal of Posthumanism, 5(5), 4327–4342. https://doi.org/10.63332/joph.v5i5.1907

[7] Bjelland, H. (2013). Engineering Safety: With applications to fire safety design of buildings and road tunnels.

[8] Bulbul, I.J., Zahir, Z., Tanvir, A., Alam, Parisha, P. (2018). Comparative study of the antimicrobial, minimum inhibitory concentrations (MIC), cytotoxic and antioxidant activity of methanolic extract of different parts of Phyllanthus acidus (l.) Skeels (family: Euphorbiaceae). World Journal of Pharmacy and Pharmaceutical Sciences. 8(1):12-57. https://doi.org/10.20959/wjpps20191-10735

[9] Carta, F., Zidda, C., Putzu, M., Loru, D., Anedda, M., & Giusto, D. (2023). Advancements in forest fire prevention: A comprehensive survey. Sensors, 23(14), 6635.

[10] Chen, C., Du, W., Xu, T. et al. Experimental study on the flame spread behavior and heat transfer model of upward-bending cable. J Therm Anal Calorim (2024). https://doi.org/10.1007/s10973-024-13248-8

[11] Chen, Y., Fang, J., Zhang, X., Miao, Y., Lin, Y., Tu, R., & Hu, L. (2023). Pool fire dynamics: Principles, models and recent advances. Progress in Energy and Combustion Science, 95, 101070.

[12] Dabous, S. A., Shikhli, A., Shareef, S., Mushtaha, E., Obaideen, K., & Alsyouf, I. (2024). Fire prevention and mitigation technologies in high-rise buildings: A bibliometric analysis from 2010 to 2023. Ain Shams Engineering Journal, 15(11), 103010.

[13] Danzi, E., Fiorentini, L., & Marmo, L. (2021). FLAME: a parametric fire risk assessment method supporting performance-based approaches. Fire Technology, 57(2), 721-765.

[14] Das, K., Tanvir, A., Rani, S. and Aminuzzaman, F.M. (2025) Revolutionizing Agro-Food Waste Management: Real-Time Solutions through IoT and Big Data Integration. Voice of the Publisher, 11, 17-36. https://doi.org/10.4236/vp.2025.111003.

[15] Deng, L., Shi, C., Xu, J., Li, H., Weng, J., & Tang, F. (2025). Forecasting the flame geometry and ground received radiative heat fluxes of two parallel adjacent fires of hydrocarbon fuel with crosswinds. International Journal of Thermal Sciences, 207, 109376.

[16] Drysdale, D. (2011). An introduction to fire dynamics. John wiley & sons.

[17] Goffer, M. A., Uddin, M. S., kaur, J., Hasan, S. N., Barikdar, C. R., Hassan, J., … Hasan, R. (2025). AI-Enhanced Cyber Threat Detection and Response Advancing National Security in Critical Infrastructure. Journal of Posthumanism, 5(3), 1667–1689. https://doi.org/10.63332/joph.v5i3.965

[18] Haldar, U., Alam, G. T., Rahman, H., Miah, M. A., Chakraborty, P., Saimon, A. S. M., Manik, M. M. T. G. (2025). AI-Driven Business Analytics for Economic Growth Leveraging Machine Learning and MIS for Data-Driven Decision-Making in the U.S. Economy. Journal of Posthumanism, 5(4), 932–957. https://doi.org/10.63332/joph.v5i4.1178

[19] Hassan, J., Barikdar, C. R., Rozario, E., Hossain, S., Ahmed, M. K., Saimon, A. S. M., & Alam, G. T. (2022). Emerging Trends and Performance Evaluation of Eco-Friendly Construction Materials for Sustainable Urban Development. Journal of Mechanical, Civil and Industrial Engineering, 2(2), 80-90. https://doi.org/10.32996/jmcie.2021.2.2.11

[20] Hassan, J., Rahman, H., Haldar, U., Sultana, S., Rahman, M. M., Chakraborty, P., … Barikdar, C. R. (2025). Implementing MIS Solutions to Support the National Energy Dominance Strategy. Journal of Posthumanism, 5(5), 4343–4363. https://doi.org/10.63332/joph.v5i5.1908

[21] Hopkin, C. (2025). Defining a maximum heat release rate probability distribution function for design fires in sprinkler-protected residential buildings. Fire and Materials, 49(1), 102-115.

[22] Hossain D., Alasa D.K, Jiyane G. (2023). Water-based fire suppression and structural fire protection: strategies for effective fire control. International Journal of Communication Networks and Information Security (IJCNIS). 15(4):485-94. Available from: https://ijcnis.org/index.php/ijcnis/article/view/7982.

[23] Hossain D., Alasa D.K. (2024a). Numerical modeling of fire growth and smoke propagation in enclosure. Journal of Management World. (5):186-96. https://doi.org/10.53935/jomw.v2024i4.1051.

[24] Hossain D., Alasa D.K. (2024b). Fire detection in gas-to-liquids processing facilities: challenges and innovations in early warning systems. International Journal of Biological, Physical and Chemical Studies. 6(2):7-13. https://doi.org/10.32996/ijbpcs.2024.6.2.2

[25] Hossain, D. (2022). Fire dynamics and heat transfer: advances in flame spread analysis. Open Access Res J Sci Technol. 2022;6(2):70-5. https://doi.org/10.53022/oarjst.2022.6.2.0061.

[26] Hossain, D. (2021). A fire protection life safety analysis of multipurpose building. Available from: https://digitalcommons.calpoly.edu/fpe_rpt/135/.

[27] Hossain, D., Asrafuzzaman, M., Dash, S., & Rani, S. (2024). Multi-Scale Fire Dynamics Modeling: Integrating Predictive Algorithms for Synthetic Material Combustion in Compartment Fires. Journal of Management World. (5): 363-374. https://doi.org/10.53935/jomw.v2024i4.1133.

[28] Hossain, E., Ashik, A. A. M., Rahman, M. M., Khan, S. I., Rahman, M. S., & Islam, S. (2023). Big data and migration forecasting: Predictive insights into displacement patterns triggered by climate change and armed conflict. Journal of Computer Science and Technology Studies, 5(4): 265–274. https://doi.org/10.32996/jcsts.2023.5.4.27.

[29] Hossain, S., Bhuiyan, M. M. R., Islam, M. S., Moniruzzaman, M., Ahmed, M. K., Das, N., Saimon, A. S. M., & Manik, M. M. T. G. (2024). Big Data Analysis and prediction of COVID-2019 Epidemic Using Machine Learning Models in Healthcare Sector. Journal of Ecohumanism, 3(8), 14468 –. https://doi.org/10.62754/joe.v3i8.6775

[30] Hossain, S., Karim, F., Sultana, S., Uddin, M., Ahmed, M. K., Chy M. A. R., … Manik, M. M. T. G. (2025). From Data to Value: Leveraging Business Analytics for Sustainable Management Practices. Journal of Posthumanism, 5(5), 82–105. https://doi.org/10.63332/joph.v5i5.1309

[31] Hossin, M. E., Rahman, M. M., Hossain, S., Siddiqa, K. B., Rozario, E., Khair, F. B., Mahmud, F. (2025). Digital Transformation in the USA Leveraging AI and Business Analytics for IT Project Success in the Post-Pandemic Era. Journal of Posthumanism, 5(4), 958–976. https://doi.org/10.63332/joph.v5i4.1180

[32] Islam, M. S., Manik, M. M. T. G., Moniruzzaman, M., Saimon, A. S. M., Sultana, S., Bhuiyan, M. M. R., … Ahmed, M. K. (2025). Explainable AI in Healthcare: Leveraging Machine Learning and Knowledge Representation for Personalized Treatment Recommendations. Journal of Posthumanism, 5(1), 1541–1559. https://doi.org/10.63332/joph.v5i1.1996

[33] Islam, S., Hossain, E., Rahman, M. S., Rahman, M. M., Khan, S. I., & Ashik, A. A. M. (2023). Digital Transformation in SMEs: Unlocking Competitive Advantage through Business Intelligence and Data Analytics Adoption. 5 (6):177-186. https://doi.org/10.32996/jbms.2023.5.6.14

[34] Johansson, N., & Svensson, S. (2019). Review of the use of fire dynamics theory in fire service activities. Fire Technology, 55, 81-103.

[35] Khair, F. B., Ahmed, M. K., Hossain, S., Hossain, S., Manik, M. M. T. G., & Rahman, R. (2024). Sustainable Economic Growth Through Data Analytics: The Impact of Business Analytics on U.S. Energy Markets and Green Initiatives," 2024 International Conference on Progressive Innovations in Intelligent Systems and Data Science (ICPIDS), Pattaya, Thailand, 2024, pp. 108-113. https://doi.org/10.1109/ICPIDS65698.2024.00026

[36] Khan, S. I., Rahman, M. S., Ashik, A. A. M., Islam, S., Rahman, M. M., & Hossain, E. (2024). Big Data and Business Intelligence for Supply Chain Sustainability: Risk Mitigation and Green Optimization in the Digital Era. European Journal of Management, Economics and Business, 1(3): 262-276. https://doi.org/10.59324/ejmeb.2024.1(3).23

[37] Khedher, N. B., Ullah, Z., Mahrous, Y. M., Dhahbi, S., Ahmad, S., Abu-Zinadah, H., & Faqihi, A. A. (2024). Viscous dissipation effect on amplitude and oscillating frequency of heat transfer and electromagnetic waves of magnetic driven fluid flow along the horizontal circular cylinder. Case Studies in Thermal Engineering, 55, 104142.

[38] Lei, B., Guo, Z., Song, C., & Guo, C. (2025). Flame instability and heat transfer effect during deflagration of premixed hydrogen in tunnel. International Journal of Thermal Sciences, 208, 109452.

[39] Li, M., & Xu, Z. (2024). Investigation of pulsating behavior and oxygen concentration of flame spread over sub-flash n-butanol fuel in a circular tube. Journal of Thermal Analysis and Calorimetry, 1-11.

[40] Liang, Y., Li, S., Chen, Y., Liu, Z., & Tian, F. (2025). Flame spread over inclined wires: The effect of molten flow behavior. Thermal Science and Engineering Progress, 58, 103181.

[41] Liu, J., Su, X., Liu, Q., Cui, X., Li, H., Gu, X., ... & Zhang, S. (2025). Constructing robust multifunctional coating on wearable nylon/cotton blend fabrics for human thermal management, motion monitoring, fire safety, and water repellency. Chemical Engineering Journal, 160658.

[42] Luo, M., Sun, X., & Li, S. (2024). A historical review of fire engineering practice and advances in China. Fire Technology, 60(2), 711-755.

[43] Ma, Y., Ren, F., Takemata, T., Nakaya, S., & Tsue, M. (2025). Near-limit downward/opposed flame spread, flame front oscillation and limiting oxygen concentration of B-LDPE tube in normal-and hypergravity. Fire Safety Journal, 152, 104329.

[44] Mahmud, F., Barikdar, C. R., Hassan, J., Goffer, M. A., Das, N., Orthi, S. M., … Hasan, R. (2025). AI-Driven Cybersecurity in IT Project Management: Enhancing Threat Detection and Risk Mitigation. Journal of Posthumanism, 5(4), 23–44. https://doi.org/10.63332/joph.v5i4.974

[45] Manik, M. M. T. G. (2020). Biotech-Driven Innovation in Drug Discovery: Strategic Models for Competitive Advantage in the Global Pharmaceutical Market. Journal of Computational Analysis and Applications (JoCAAA), 28(6), 41–47. Retrieved from https://eudoxuspress.com/index.php/pub/article/view/2874

[46] Manik, M. M. T. G. (2021). Multi-Omics System Based on Predictive Analysis with AI-Driven Models for Parkinson's Disease (PD) Neurosurgery. Journal of Medical and Health Studies, 2(1), 42 - 52. https://doi.org/10.32996/jmhs.2021.2.1.5

[47] Manik, M. M. T. G. (2022). An Analysis of Cervical Cancer using the Application of AI and Machine Learning. Journal of Medical and Health Studies, 3(2), 67-76. https://doi.org/10.32996/jmhs.2022.3.2.11

[48] Manik, M. M. T. G. (2023). Multi-Omics Integration with Machine Learning for Early Detection of Ischemic Stroke Through Biomarkers Discovery. Journal of Ecohumanism, 2(2), 175 –187. https://doi.org/10.62754/joe.v2i2.6800

[49] Manik, M. M. T. G. (2025). Integrative Analysis of Heterogeneous Cancer Data Using Autoencoder Neural Networks. Vol.10 No. 3s (2025), 548-554. https://doi.org/10.52783/jisem.v10i3s.4746

[50] Manik, M. M. T. G., Bhuiyan, M. M. R., Moniruzzaman, M., Islam, M. S., Hossain, S., & Hossain, S. (2018). The Future of Drug Discovery Utilizing Generative AI and Big Data Analytics for Accelerating Pharmaceutical Innovations, Nanotechnology Perceptions, Vol.14, No. 3 (2018), 120-135.https://doi.org/10.62441/nano-ntp.v14i3.4766

[51] Manik, M. M. T. G., Hossain, S., Ahmed, M. K., Rozario, E., Miah, M. A., Moniruzzaman, M., Islam, M. S., & Saimon, A. S. M. (2022). Integrating Genomic Data and Machine Learning to Advance Precision Oncology and Targeted Cancer Therapies. Nanotechnology Perceptions, Vol. 18 No. 2 (2022), 219-243, https://doi.org/10.62441/nano-ntp.v18i2.5443

[52] Manik, M. M. T. G., Mohonta, S. C., Karim, F., Miah, M. A., Islam, M. S., Chy M. A. R., Saimon, A. S. M. (2025). AI-Driven Precision Medicine Leveraging Machine Learning and Big Data Analytics for Genomics-Based Drug Discovery. Journal of Posthumanism, 5(1), 1560–1580. https://doi.org/10.63332/joph.v5i1.1993

[53] Manik, M. M. T. G., Moniruzzaman, M., Islam, M. S., Bhuiyan, M. M. R., Rozario, E., Hossain, S., Ahmed, M. K., & Saimon, A. S. M. (2020). The Role of Big Data in Combatting Antibiotic Resistance Predictive Models for Global Surveillance, Nanotechnology Perceptions, Vol. 16 No. 3 (2020), 361-378, https://doi.org/10.62441/nano-ntp.v16i3.5445

[54] Manik, M. M. T. G., Saimon, A. S. M., Islam, M. S., Moniruzzaman, M., Rozario, E., & Hossin, M. E. (2025). Big Data Analytics for Credit Risk Assessment. In 2025 International Conference on Machine Learning and Autonomous Systems (ICMLAS), Prawet, Thailand, 2025, pp. 1379-1390, https://doi.org/10.1109/ICMLAS64557.2025.10967667

[55] Manik, M. M. T. G., Saimon, A. S. M., Miah, M. A., Ahmed, M. K., Khair, F. B., Moniruzzaman, M., Islam, M. S., & Bhuiyan, M. M. R. (2021). Leveraging Ai-Powered Predictive Analytics for Early Detection of Chronic Diseases: A Data-Driven Approach to Personalized Medicine. Nanotechnology Perceptions, Vol. 17 No. 3 (2021), 269-288, https://doi.org/10.62441/nano-ntp.v17i3.5444

[56] McGrattan, K., McDermott, R., Floyd, J., Hostikka, S., Forney, G., & Baum, H. (2012). Computational fluid dynamics modelling of fire. International journal of computational fluid dynamics, 26(6-8), 349-361.

[57] Miah, M. A., Ahmed, M. K., Bhuiyan, M. M. R., Chy M. A. R., Khair, F. B., Uddin, M., Manik, M. M. T. G. (2025). Big Data Analytics for Enhancing Coal-Based Energy Production Amidst AI Infrastructure Growth. Journal of Posthumanism, 5(5), 5061–5080. https://doi.org/10.63332/joph.v5i5.2087.

[58] Miah, M. A., Rozario, E., Khair, F. B., Ahmed, M. K., Bhuiyan, M. M. R., & Manik, M. M. T. G. (2019). Harnessing Wearable Health Data and Deep Learning Algorithms for Real-Time Cardiovascular Disease Monitoring and Prevention, Nanotechnology Perceptions, Vol. 15 No. 3 (2019), 326-349. https://doi.org/10.62441/nano-ntp.v15i3.5278.

[59] Moniruzzaman, M., Islam, M. S., Mohonta, S. C., Adnan, M., Chy M. A. R., Saimon, A. S. M., … Manik, M. M. T. G. (2025). Big Data Strategies for Enhancing Transparency in U.S. Healthcare Pricing. Journal of Posthumanism, 5(5), 3744–3766. https://doi.org/10.63332/joph.v5i5.1813

[60] Negi, P., Pathani, A., Bhatt, B. C., Swami, S., Singh, R., Gehlot, A., ... & Sikarwar, V. S. (2024). Integration of Industry 4.0 Technologies in Fire and Safety Management. Fire, 7(10), 33

[61] Parmar, P., Mukherjee, S., & Meikap, B. C. (2024). Comprehensive Analysis on the Combined Effects of Reaction Kinetics and Heat Transfer on Biomass Pyrolysis. Process Safety and Environmental Protection.

[62] Pyne, S. J. (2022). The Pyrocene: How we created an age of fire, and what happens next. Univ of California.

[63] Rahman, M. S., Islam, S., Khan, S. I., Ashik, A. A. M., Hossain, E., & Rahman, M. M. (2024). Redefining marketing and management strategies in digital age: Adapting to consumer behavior and technological disruption. Journal of Information Systems Engineering and Management, 9(4): 1–16. https://doi.org/10.52783/jisem.v9i4.32

[64] Shabanlou, M., Mofid, M., Eslami, M., Kodur, V., Meghdadi, Z., & Tavakoli, A. (2025). Experimental, analytical and numerical investigation on the effects of different shear reinforcement on residual post-fire behavior of reinforced concrete deep beams. Structure and Infrastructure Engineering, 1-18.

[65] Shi, X., Ren, X., Zhang, Y., Chen, S., Li, Y., Li, S., ... & Cao, W. (2025). Dynamic characteristics and response mechanism of pool fire under external acoustic excitation. Thermal Science and Engineering Progress, 103279.

[66] Singh, H., Ang, L. M., Lewis, T., Paudyal, D., Acuna, M., Srivastava, P. K., & Srivastava, S. K. (2024). Trending and emerging prospects of physics-based and ML-based wildfire spread models: A comprehensive review. Journal of Forestry Research, 35(1), 135.

[67] Soares, I., Ferreira, J. L., Silva, H., & Rodrigues, M. P. (2024). Fire-retardant and fire-resistant coatings: From industry to the potential use on cultural heritage. Journal of Cultural Heritage, 68, 316-327.

[68] Sultana, S., Karim, F., Rahman, H., Chy M. A. R., Uddin, M., Khan, M. N., Hossin, M. E., & Rozario, E. (2024). A Comparative Review of Machine Learning Algorithms in Supermarket Sales Forecasting with Big Data. Journal of Ecohumanism, 3(8), 14457 –. https://doi.org/10.62754/joe.v3i8.6762

[69] Sun, J., Speer, K., Quaife, B., Cai, M., & Schvartzman, D. (2025). The Turbulent Plume from Wildland Fire in Sheared Boundary Layer Flow. arXiv preprint arXiv:2501.08343.

[70] Tanvir, A.; Jo, J.; Park, S.M. Targeting Glucose Metabolism: A Novel Therapeutic Approach for Parkinson's Disease. Cells. 2024, 13, 1876. https://doi.org/10.3390/cells13221876

[71] Zang, X., Liu, W., Wu, D., Pan, X., Zhang, W., Bian, H., & Shen, R. (2023). Contemporary fire safety engineering in timber structures: Challenges and solutions. Fire, 7(1), 2.

[72] Zhang, N., Pan, X., Yang, J., Liu, Q., Lian, W., Du, X., ... & Guan, G. (2024). Simulation of gas-solids heat transfer in cyclone pyrolyzer using CFD-DEM model. Particuology, 85, 155-166.

[73] Zhang, X., Kuang, S., Zhao, Y., Deng, Y., Luo, S., & Wang, P. (2025). Study on the Critical Flame Spread Along Inclined and Discrete Thermally-Thin Paper. Fire Technology, 1-21.

[74] Zhijie, Z. (2024). Advancements in Forest Fire Monitoring and Management: Insights from Canadian Research and Global Perspectives. Journal of Natural and Life Sciences. (1):20-24.