



A SYSTEMATIC REVIEW ON THE IMPACT OF NFPA-COMPLIANT FIRE PROTECTION SYSTEMS ON U.S. INFRASTRUCTURE RESILIENCE

Md. Milon Mia¹

[1]. Department of Civil & Environmental Engineering, Lamar University, Beaumont, Texas , USA.
Email: milon674457@gmail.com

Doi: [10.63125/ne3ey612](https://doi.org/10.63125/ne3ey612)

This work was peer-reviewed under the editorial responsibility of the IJBEI, 2025

Abstract

This systematic review evaluates how NFPA-compliant fire protection systems contribute to infrastructure resilience in the United States by linking code-conforming design and maintenance to measurable outcomes. Following PRISMA 2020, we searched major databases and grey sources, screened records in duplicate, extracted standardized measures, appraised risk of bias, and synthesized evidence using random effects and narrative methods. In total, 115 studies met the inclusion criteria, spanning healthcare, industrial and energy facilities, transportation tunnels and stations, data centers, and high-rise residential and commercial buildings. Across the corpus, verified compliance and disciplined inspection, testing, and maintenance were consistently associated with better life-safety and continuity outcomes, including higher odds of confinement to room or area of origin, lower injuries and direct losses, reduced nuisance alarms, and shorter downtime. Paired systems performed best; detection with automatic suppression yielded additive gains, and smoke management improved egress tenability under door-open conditions. Moderators included governance quality, building vintage, hazard severity, and water or power redundancy. Framed through robustness, redundancy, resourcefulness, and rapidity, findings show that NFPA-aligned hardware governed by auditable compliance and maintenance functions as an engineered risk control that compresses severe-event tails and accelerates recovery. Economic signals from studies reporting business interruption aligned with physical loss containment, supporting favorable present-value cases for sustained compliance and maintenance programs. Practically, the review recommends outcome-oriented acceptance testing tuned to credible scenarios, portfolio dashboards tracking confinement and restoration metrics, and prioritization of high-leverage components such as pumps, supervisory valves, detection networks, and smoke control interfaces to deliver reliable, sector-specific resilience gains.

Keywords

NFPA Compliance; Fire Protection Systems; Infrastructure Resilience; Automatic Sprinklers; Fire Detection and Alarm; Smoke Control;

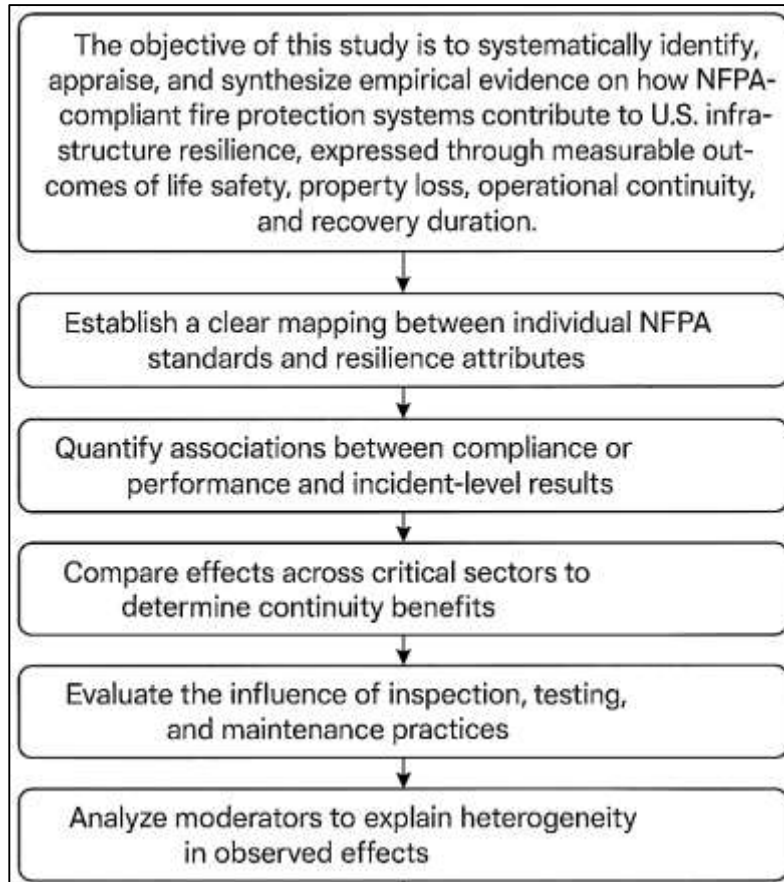
INTRODUCTION

Fire protection systems are the ensemble of active, passive, and organizational measures that reduce fire growth, limit untenable conditions, and protect people and assets; they include automatic sprinklers and standpipes (e.g., NFPA 13), water supplies and pumps (NFPA 20), inspection, testing, and maintenance (ITM) regimes for water-based systems (NFPA 25), and detection, notification, and signaling systems (NFPA 72), alongside life-safety provisions such as egress and compartmentation addressed in NFPA 101. In the hazards and infrastructure literature, “resilience” denotes the capacity of systems to absorb disturbance, sustain essential function, and recover performance in a timely manner; the widely used 4R framework (robustness, redundancy, resourcefulness, rapidity) operationalizes this construct into measurable attributes (Bruneau et al., 2003). These definitional anchors enable a direct mapping between code-conforming fire protection design/maintenance and resilience metrics used for critical infrastructure, where robustness arises from engineered reliability (e.g., automatic suppression activation thresholds and alarm audibility), redundancy from overlapping means (e.g., parallel water supplies, multi-sensor detection), resourcefulness from codified ITM practices, and rapidity from shortened time-to-notification, time-to-suppression, and time-to-stabilization (Bruneau et al., 2003). A large body of empirical and modeling work shows that when smoke alarms and sprinklers are present and functional, reported fires and casualties decrease substantially and fire spread is more often confined to room or area of origin (Butry, 2009, 2012). In U.S. infrastructure spanning healthcare facilities, industrial plants, transportation hubs, data centers, higher-education laboratories, and high-rise commercial buildings code-conforming fire protection systems therefore form a technical substrate for resilience that connects device-level performance to continuity metrics such as downtime, restoration time, and business interruption losses (Festag, 2021). Definitional clarity further requires expressing “resilience” with variables observable in fire incidents and post-event recovery. Robustness is made tangible through system reliability and availability on demand (e.g., probability that a sprinkler head opens and delivers design density at ignition growth conditions), redundancy by functional overlap (e.g., detection that actuates suppression and also triggers smoke management), resourcefulness by preventive and corrective maintenance embedded in NFPA 25’s ITM frequencies, and rapidity by time-based outcomes such as alarm notification time, suppression activation time, incident stabilization time, and the duration from event to re-occupancy (Bruneau et al., 2003). Quantitative studies estimate, for example, that installing smoke alarms in previously unalarmed homes reduces the expected number of fires reported from those residences by roughly 70–80% and casualties by 60–70% (NIST, 2018). Review syntheses of sprinkler performance consistently document high operation and effectiveness rates across methodologies (component-based reliability models and system-level incident datasets) (Frank et al., 2013), while observational work links sprinklers and smoke control measures to reduced damage metrics in real fires (Danish & Md. Zafar, 2022; Festag, 2021). The conceptual elegance here is pragmatic: each NFPA-conforming subsystem modifies the fire growth curve and occupant/asset exposure in ways that track directly onto resilience attributes, making resilience an inferable property from measurable protection performance (Danish & Kamrul, 2022; Santos et al., 2017).

The international significance of these relationships is twofold. First, although NFPA standards are developed within a U.S. consensus process, they are referenced, adopted, or used as benchmarks worldwide, and their underlying engineering logic (e.g., sprinkler density selection, fire pump reliability, alarm audibility/visibility) is not jurisdiction-limited (Gilbert, 2021; Jahid, 2022a). Second, a cross-national evidence base strengthens generalizability: large-sample European studies using incident data demonstrate that installed technical measures detection and alarm, extinguishing systems, and smoke and heat exhaust are each statistically associated with lower damage outcomes, echoing North American findings on life loss and property loss reduction (Festag, 2021; Jahid, 2022b). Complementary epidemiologic and public-health research across decades indicates that smoke alarm presence and function is associated with lower fatality risk and injury rates (Istre et al., 2001; Arifur & Noor, 2022). These population-level signals provide an external validity check on engineering analyses that estimate, for instance, alarm detection times at low heat release rates or sprinkler control before flashover. When interpreted through the 4R lens, the international literature implies that code-conforming protection can be read as a resilience intervention: robustness (fewer high-intensity events),

redundancy (fewer single-point failures), resourcefulness (sustained readiness through ITM), and rapidity (shorter event and recovery durations) (Benveniste & Nemati, 2014; Bruneau et al., 2003; Hasan et al., 2022).

Figure 1: NFPA-conforming fire protection systems



Mechanistically, NFPA-conforming systems affect the physics and logistics of fire events in measurable ways. Automatic sprinklers, designed per NFPA 13, limit heat release and delay or prevent flashover; water-mist variants documented in the literature achieve additional cooling and oxygen displacement effects desirable in sensitive occupancies (Mawhinney & Richardson, 1997; Redwanul & Zafor, 2022). Detection and alarm per NFPA 72 improve time-to-awareness, which increases available safe egress time and triggers response actions. Reliability studies of pumps, valves, and distribution networks show that availability on demand and during fire-fighting depends on ITM intervals and component configurations characteristics codified in NFPA 25 (Rezaul & Mesbaul, 2022; Santos et al., 2017). Empirical syntheses and econometric analyses demonstrate the downstream effects: installing smoke alarms in low-penetration areas reduces incident reporting and casualties (Hasan, 2022; NIST, 2018), and sprinklers produce consistent reductions in death, injury, and loss controlling for confounders (Butry, 2009). Smoke management and pressurization systems are likewise associated with improved evacuation conditions by limiting smoke spread and maintaining tenability in egress routes (Kang & Lee, 2017; Tarek, 2022). In aggregate, these mechanisms show how code-conforming design (density selection, response times, redundancy) and maintenance (functional testing, impairment control) translate into performance states aligned with resilience attributes without invoking speculative forecasting (Mawhinney & Richardson, 1997; Kamrul & Omar, 2022).

Sectoral contexts in the United States clarify the resilience lens because tolerance for disruption is heterogeneous. In healthcare occupancies, where NFPA 99 and NFPA 101 converge on layered protection (compartmentation, staff response, detection, suppression), the combined effect of early warning and rapid suppression confines many incidents to small compartments, protecting vulnerable patients and complex equipment; while randomized trials are infeasible, convergence of

detection/suppression effectiveness studies supports this interpretation (Frank et al., 2013; Mallonee et al., 1996). In high-reliability facilities data centers and telecom hubs automatic suppression and smoke management are integral to continuity, as even short outages cascade into broader service disruptions; modeling frameworks that tie heat release rate reduction and smoke control to reduced damage footprints make the continuity linkage observable (Istre et al., 2001; Kamrul & Tarek, 2022). In high-rise residential/commercial buildings, stair pressurization and smoke control performance under door-open conditions have been shown via computational and experimental studies to influence shaft tenability, directly affecting egress duration and incident stabilization timelines (Kang & Lee, 2017; Mubashir & Abdul, 2022; Wang et al., 2021). For industrial/process and storage occupancies, sprinkler research across commodity classes (including large-drop and ESFR heritage) provides an engineering basis for risk-appropriate densities and system configurations that curtail high-consequence events (Hurley et al., 2016). Across sectors, the same pattern holds: NFPA-conforming systems are the proximate levers by which the hazard is moderated and continuity preserved (Frank et al., 2013; Muhammad & Kamrul, 2022).

The economic literature complements the engineering evidence by translating loss reductions into benefit-cost terms and by linking damage footprints to business interruption durations variables that infrastructure resilience scholars often treat as recovery time distributions. Residential sprinkler analyses have repeatedly found favorable net benefits once avoided fatalities, injuries, and property losses are monetized (Butry, 2009; Reduanul & Shoeb, 2022), a result conceptually consistent with broader valuation frameworks such as the life-quality index and the value of statistical life (Noor & Momena, 2022; Viscusi & Aldy, 2003), and aligned with later work applying cost-benefit methods to sprinkler decisions in housing (e.g., Fire Safety Journal applications). At facility scale, component-based recovery models from allied hazards formalize how repair scope, utility dependencies, and inspection/commissioning sequences propagate into total downtime; when paired with empirical findings that early detection and suppression truncate severity, these frameworks imply shorter tails in restoration times for protected facilities (Bruneau et al., 2003; Danish, 2023). The statistical relationship between protection presence/function and lower losses (Frank et al., 2013) therefore carries a direct economic meaning: reductions in damage translate into narrower variance in interruption durations, enabling continuity planning to be grounded in observed performance rather than assumption sets (Butry, 2009; Hasan et al., 2023).

Governance of design, installation, and maintenance is itself an essential part of the resilience construct because reliability is a function not just of hardware quality but also of oversight, documentation, and timely remediation of impairments. Fault-tree and reliability-block-diagram analyses of fire pump power supply configurations, for example, quantify improvements from alternate feeds and on-site generation, underscoring the resilience contribution of redundancy and preventive maintenance (Gilbert, 2021; Hossain et al., 2023). Availability modeling for pumps under periodic inspection shows that NFPA-style ITM cycles materially influence availability on demand and during combat (Santos et al., 2017). On the detection side, population-based epidemiology and national assessments demonstrate that presence and function of alarms are associated with lower mortality and injury, but they also document non-trivial rates of non-functionality that make inspection/testing more than a mere compliance exercise (Istre et al., 2001; Uddin & Ashraf, 2023). Smoke control studies in high-rise and underground settings further reveal sensitivity to maintenance states (e.g., damper leakage), linking equipment condition to egress tenability (Runyan et al., 1992). In sum, codified processes for ITM, impairment tracking, and documentation central features of NFPA standards constitute the organizational backbone through which device-level reliability aggregates into system-level resilience in U.S. infrastructure (Momena & Hasan, 2023; Runyan et al., 1992). Finally, because infrastructure resilience is evaluated on observable outcomes rather than aspirational goals, this introduction foregrounds measurable links between NFPA-conforming fire protection systems and resilience metrics across U.S. settings. The literature used here spanning community-level epidemiology, national statistical modeling, engineering reliability analysis, and review syntheses allows the research questions of this paper to be framed without recourse to conjecture: presence and function of detection and suppression systems are associated with lower casualty and loss rates; ITM affects availability and

therefore performance; smoke management influences egress tenability; and these changes in event severity and extent are analytically identical to the resilience attributes of robustness, redundancy, resourcefulness, and rapidity. The following sections of the paper adopt a systematic-review method to collect, appraise, and synthesize this evidence base with attention to study design, measure comparability, and sectoral context (Mallonee et al., 1996; Runyan et al., 1992; Viscusi & Aldy, 2003). The objective of this study is to systematically identify, appraise, and synthesize empirical evidence on how NFPA-compliant fire protection systems contribute to U.S. infrastructure resilience, expressed through measurable outcomes of life safety, property loss, operational continuity, and recovery duration. Specifically, the review aims to: establish a clear mapping between individual NFPA standards and system types such as detection and alarm, automatic sprinklers and standpipes, fire pumps and water supplies, smoke management and egress and the resilience attributes of robustness, redundancy, resourcefulness, and rapidity; quantify the direction and magnitude of associations between compliance or functional performance and incident-level results including fire growth limitation, confinement to origin, casualty reduction, damage intensity, downtime hours, and time to restoration; compare effects across critical sectors (healthcare, industrial/process, energy and utilities, transportation facilities, data centers and telecommunications, high-rise residential and commercial) to determine where compliance yields the strongest continuity benefits; evaluate the influence of inspection, testing, and maintenance practices and impairment management on system availability on demand and during firefighting, thereby distinguishing design adequacy from upkeep-driven reliability; analyze moderators such as building vintage, occupancy load, hazard severity, redundancy of water supply, and enforcement intensity to explain heterogeneity in observed effects; assess the methodological quality and risk of bias of included studies and, where data permit, estimate pooled effect sizes and heterogeneity through meta-analytic techniques complemented by sensitivity and subgroup analyses; construct an evidence map that links standards, sectors, and outcome domains to reveal concentration, gaps, and consistency of findings; and translate the synthesized results into a transparent dataset of effect metrics, operational definitions, and coding decisions that can support replication and future decision analyses. The overarching goal is to deliver a rigorous, literature-driven account of whether, where, and to what extent code-conforming fire protection systems reduce adverse fire outcomes and shorten restoration timelines in U.S. infrastructure, doing so through a reproducible protocol that privileges comparability of measures, clarity of inclusion criteria, and traceability from study-level data to aggregated conclusions.

LITERATURE REVIEW

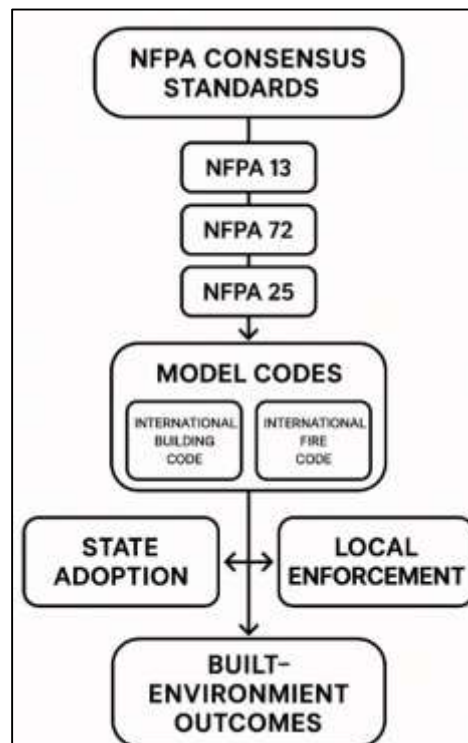
The literature on NFPA-compliant fire protection systems spans engineering design studies, reliability and availability analyses, full-scale and reduced-scale experiments, incident statistics, epidemiological evaluations, and economic appraisals, yet the findings are dispersed across journals, technical reports, and sector-specific case work. This review opens by consolidating the core strands that connect code-conforming design and maintenance to infrastructure resilience. First, research on active systems detection/notification, automatic sprinklers and standpipes, fire pumps and water supplies characterizes how configuration, actuation thresholds, and hydraulic performance shape early fire dynamics and occupant tenability. Second, work on passive protection and egress compartmentation, smoke control, pressurization, wayfinding examines conditions in vertical transportation paths and areas of refuge that influence incident stabilization and evacuation duration. Third, inspection, testing, and maintenance (ITM) scholarship evaluates the availability of systems on demand and during firefighting, distinguishing design adequacy from upkeep-driven reliability and impairment management. Across these strands, the literature operationalizes resilience through observable outcomes: life safety (fatalities, injuries), loss metrics (direct damage per unit area or value), operational continuity (downtime hours, service disruptions), and recovery duration (time to re-occupancy or restoration of function). Methodologically, studies range from controlled experiments and computational fluid dynamics to observational incident databases, quasi-experimental comparisons, and benefit-cost models; each approach carries distinct sources of bias and comparability challenges, notably in the measurement of compliance, the verification of system functionality at the time of the event, and the normalization of outcomes across occupancies and hazard severities. Sector heterogeneity healthcare, industrial/process, energy and utilities, transportation facilities, data centers

and telecommunications, and high-rise residential/commercial introduces moderators such as building vintage, redundancy of water supply, equipment criticality, and enforcement intensity. The introductory synthesis therefore lays out a crosswalk that maps systems and standards to outcome domains and specifies the variables required for transparent comparison: presence and type of protection, compliance verification method, ITM frequency and findings, impairment records, fire growth indicators, smoke conditions, confinement measures, and continuity metrics. It also establishes decision rules for handling study quality, missing data, and overlapping datasets. With this structure, the literature review proceeds to evaluate the direction and magnitude of effects, the consistency of signals across methods and sectors, and the explanatory value of moderators, setting the stage for evidence mapping and, where feasible, meta-analytic estimation in subsequent subsections.

NFPA Standards Landscape and Code Pathways

The United States fire- and life-safety regulatory environment is a multi-layered ecosystem in which NFPA consensus standards interface with model building and fire codes, state adoption processes, and local enforcement practices. At its core, the “pathway” from technical standard to built-environment outcome begins with the development of NFPA documents (for example, NFPA 13 for sprinklers, NFPA 72 for fire alarm and signaling, and NFPA 25 for inspection, testing, and maintenance), which are then referenced directly or indirectly by model codes such as the International Building Code (IBC) and International Fire Code (IFC) or by NFPA 5000 in some jurisdictions. Contemporary scholarship frames this apparatus as a socio-technical system, emphasizing that codes and standards are only one component within a web of institutions, market actors, professional competencies, and public values that collectively determine performance in the real world (Meacham et al., 2021; Mubashir & Jahid, 2023). Within this socio-technical lens, pathways are not linear: the same NFPA requirement can produce different risk reductions depending on adoption cycles, local amendments, the capacity of authorities having jurisdiction (AHJs), and how performance-based alternatives are handled during design and approval (Meacham & Straalen, 2017; Sanjai et al., 2023). Equally, the rise of performance-based fire safety engineering complicates the pathway by allowing engineered equivalencies that must still remain consistent with the life-safety intent baked into referenced NFPA criteria (Akter et al., 2023; Tavares, 2009). Together, these dynamics make the standards landscape both robust and heterogeneous capable of high performance when implemented with fidelity, yet sensitive to gaps in adoption, interpretation, and maintenance (Danish & Zafor, 2024; Lange et al., 2014; Tavares, 2009).

Figure 2: NFPA Standards Landscape and Code Pathways



Environment Outcomes

A second layer in the pathway concerns how model codes import NFPA requirements and how AHJs operationalize them through plan review, permitting, and inspection. Research shows that even when identical prescriptive references exist on paper, realized safety is conditioned by the quality of hazard characterization, the treatment of design fires, and the competence with which performance objectives are translated into verifiable criteria areas where NFPA's prescriptive clarity can interact uneasily with project-specific performance claims (Gernay, 2016). The structural fire-engineering literature illustrates this tension: traditional uniform-temperature design fires implicit in many code pathways can underestimate or mischaracterize risks in large, open compartments, whereas performance-based approaches (often advanced under code provisions allowing engineering judgment) must address travelling-fire phenomena and non-uniform heating to remain consistent with intended safety margins. These scientific insights feed back into the standards ecosystem via committees and code-change cycles, but the diffusion into everyday practice hinges on AHJ bandwidth and clear acceptance criteria. Empirical and review studies have therefore argued for risk-informed, reliability-consistent pathways that connect NFPA technical provisions with explicit performance targets, improving traceability from the standard to the expected societal risk reduction. In short, the pathway is strongest where NFPA prescriptions, model-code adoptions, and performance-based alternatives are integrated under explicit, agreed risk metrics with adequate enforcement capacity (Tavares, 2009).

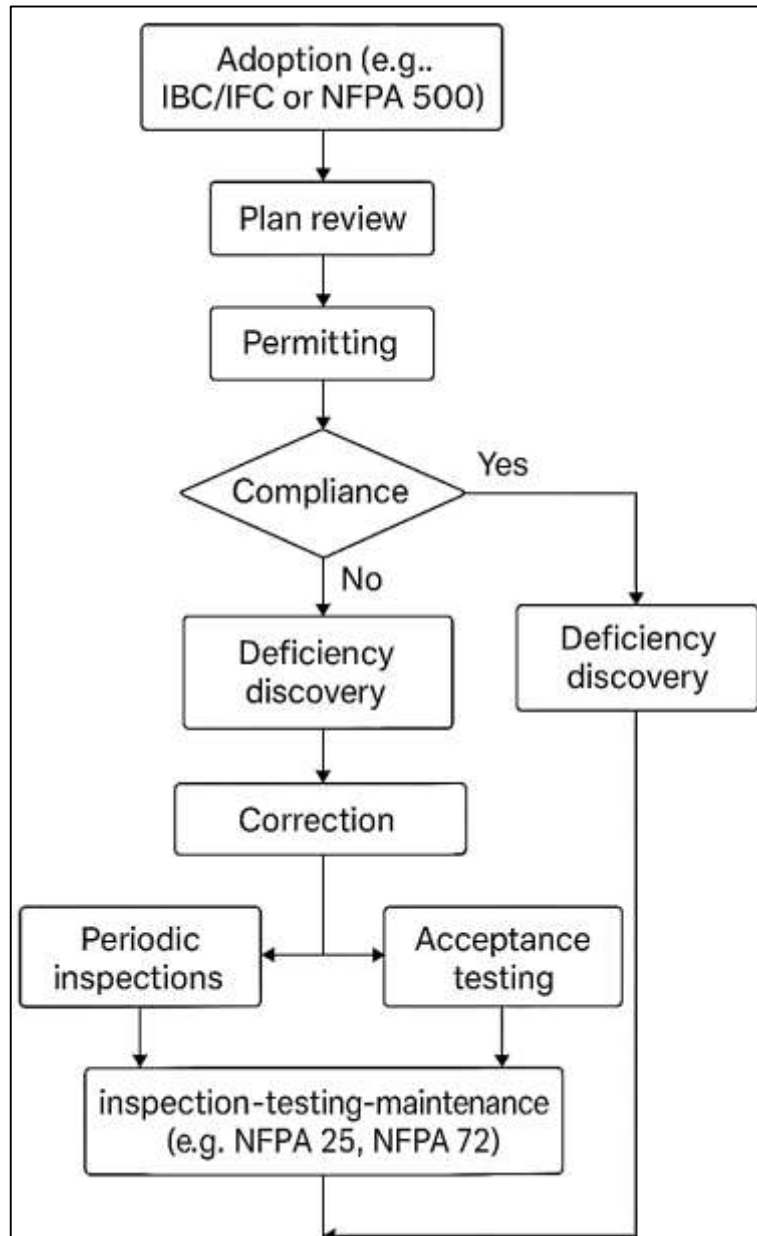
Finally, the "last mile" in the pathway adoption and enforcement determines whether NFPA-compliant systems deliver resilient outcomes across communities (Jahid, 2024a). Studies of code effectiveness grading and participation show uneven engagement with programs intended to incentivize stringent adoption and strong enforcement, revealing a patchwork of local capacities that can attenuate the benefits of advanced NFPA provisions (Building Code Effectiveness Grading Schedule participation analysis: 10.1108/IJDRBE-01-2020-0004). Parallel work in probabilistic structural fire engineering underscores that without consistent compliance and maintenance including adherence to NFPA ITM standards the reliability of fire protection strategies and structural performance cannot be assured, particularly under non-stationary or complex fire exposures (Lange et al., 2014; Torero et al., 2024; Van Coile et al., 2021). Recent scholarship proposes anchoring pathways in explicit risk-based objectives so that prescriptive references to NFPA documents, performance-based alternatives, and operational controls (e.g., NFPA 25 programs) all map to transparent target reliabilities and decision criteria. Complementing this, advances in understanding travelling-fire demands (Dai et al., 2017) and in hazard-based, reliability-consistent design (Jahid, 2024b) provide technical mechanisms to close the loop between codes and real performance. Collectively, these strands indicate that the pathway from NFPA standard to resilient infrastructure is both technically and institutionally contingent: it succeeds where adoption is current, enforcement is capable, and performance claims are tied to the same risk and reliability fabric that underpins the NFPA consensus process (Dai et al., 2017).

Compliance and System Availability Pathways

Compliance and enforcement are the mechanisms that convert NFPA prescriptions into operational reliability at the moment of demand. Across jurisdictions, the pathway typically begins with code adoption (e.g., IBC/IFC or NFPA 5000) and proceeds through plan review, permitting, periodic inspections, acceptance testing, and recurring inspection-testing-maintenance (ITM) under standards such as NFPA 25 and NFPA 72. Empirical and methodological literature emphasizes that "paper compliance" must be distinguished from function-on-demand, with availability governed by ITM quality, impairment management, and closure of findings (front-line execution by owners/contractors and oversight by Authorities Having Jurisdiction, AHJs). Case-based compliance assessment tools developed for workplaces and education facilities demonstrate how codified checklists and risk-weighted scoring can raise detection of deficiencies, reduce inspector subjectivity, and improve traceability from requirement to control (Alhazmi et al., 2022; Fowler & Sadiq, 2025). At the same time, socio-institutional research on adoption/enforcement finds persistent heterogeneity among AHJs budget, staffing, inspector qualifications, and clarity of acceptance criteria which mediates realized safety even where codes reference the same NFPA provisions (Jansen et al., 2021; Hasan, 2024). Where enforcement bandwidth is constrained, automated and semi-automated approaches ontology-driven rule checking and blueprint-level risk flagging are proposed to pre-screen designs against fire code

logic and route high-risk issues to human review, offering a complementary pathway to keep compliance workloads aligned with modern, complex systems (El-Sawalhi & Mosa, 2021; Li et al., 2022). Together, these strands frame enforcement not as a single event but as a reliability process: adoption establishes intent, ITM sustains readiness, impairment programs minimize exposure windows, and AHJ oversight closes the loop from deficiency discovery to verified correction (Bonsi et al., 2023; Jahid, 2025b).

Figure 3: Compliance, enforcement, and system availability pathways



Evidence on availability and reliability shows that enforced ITM materially influences failure probabilities in active systems. Quantitative reliability models fault-tree, Bayesian, and dynamic fault-tree analyses reveal the dominant failure modes and the risk leverage points addressable by NFPA-25-style programs (Jahid, 2025a; Ismail et al., 2025; Jakaria et al., 2025). Survey-based component reliability and high-rise field data further indicate that wet-pipe sprinkler reliability deteriorates in the absence of disciplined testing, valve supervision, and water-supply monitoring; conversely, programs with documented ITM and managed impairments sustain high probabilities of successful operation (El-Sawalhi & Mosa, 2021; Tannous et al., 2016). On the detection side, controlled and quasi-experimental studies show that inspection/installation programs increase the presence and operability of smoke

alarms, but also that benefits erode without maintenance and revisit protocols underscoring the enforcement role of periodic verification and owner education (Alshammari et al., 2022). Meta-analytic work on smoke alarms reports large mortality reductions associated with working devices, reinforcing why enforcement should couple initial compliance (installation/acceptance) with mechanisms that sustain functionality over time (DiGuiseppi et al., 2002; Hasan, 2025; Zafar, 2025). In parallel, tunnel and special-occupancy research demonstrates that compliance cannot be judged solely by presence of equipment; acceptance testing, scenario-appropriate performance verification, and periodic re-tests are needed to ensure that systems perform under the actual demand envelopes implied by the occupancy (Givehchi & Heidari, 2019; Uddin, 2025). Collectively, these studies justify enforcement architectures that prioritize high-impact components and events e.g., valves left shut, pumps not started, detectors not cleaned because small lapses at these nodes disproportionately degrade system availability at the incident.

Finally, impairment management policies translate enforcement into day-to-day resilience. The literature distinguishes between planned, emergency, and hidden impairments; all three expand loss potential unless durations are minimized and compensatory measures (fire watch, hot-work controls, hazard reduction) are documented and verified (Givehchi & Heidari, 2019; Sanjai et al., 2025). Economic and program-evaluation studies reinforce that structured inspections and home-visitation models are cost-effective when they raise the share of functioning protection and reduce time-until-restoration, but only if design-stage compliance is paired with persistent operational oversight (Givehchi & Heidari, 2019). Emerging governance work in the U.S. shows that AHJs cite funding, staffing, and political support as core constraints to adopting and enforcing the latest codes; targeted federal and state incentives for enforcement capacity, shared services, and digital inspection infrastructure are identified as levers that can narrow inter-jurisdictional disparities (DiGuiseppi et al., 2002). In design review, AI-assisted and ontology-based compliance checking can triage routine conformance tasks, freeing AHJs to focus on performance-critical judgments and complex equivalencies (Bonsi et al., 2023). When these administrative and technical elements align current code adoption, risk-prioritized inspection schedules, documented ITM under NFPA 25/72, disciplined impairment programs, and measurable closure rates compliance and enforcement mechanisms act as a reliability amplifier, increasing the likelihood that NFPA-compliant systems actually operate and thereby strengthening the resilience attributes of robustness, redundancy, resourcefulness, and rapidity across U.S. infrastructure.

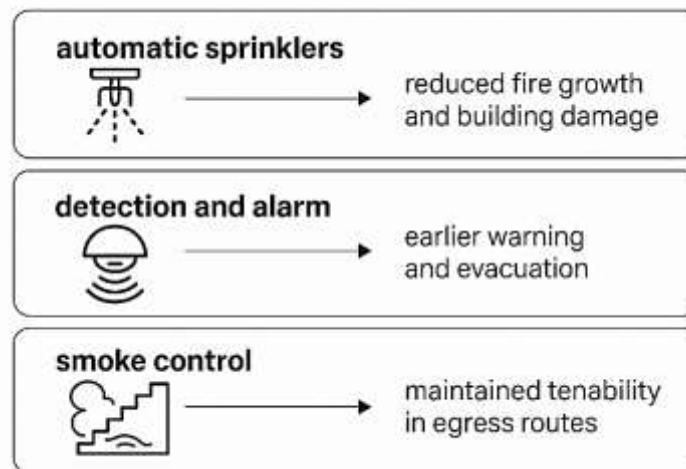
System Types and Performance Evidence

Across active fire protection technologies, empirical and experimental evidence consistently shows that correctly designed and maintained systems change fire growth, tenability, and loss trajectories in ways that align with resilience attributes of robustness and rapidity. Automatic sprinklers are the clearest case: incident-based comparisons demonstrate large reductions in fire area escalation and building fabric damage once fires exceed small sizes, indicating that sprinklers substantially lower the probability that a fire progresses beyond the room of origin (Yu, 2012). Complementary laboratory and scale-model programs clarify how spray momentum, droplet size distributions, and ventilation interact to determine suppression time and required discharge densities, especially for fine sprays and water mist in enclosures (Melinek, 1993). For water-mist systems, scaling studies show that performance is sensitive to penetration and mixing under deep-seated solid fuel fires, which in turn depend on door opening geometry and nozzle arrays mechanistic findings that explain why some field deployments succeed while others underperform (Zhang & colleagues, 2019). Clean-agent systems used to protect mission-critical spaces (e.g., data centers, control rooms) add a different risk-reduction pathway: inert gases and fluorinated ketones achieve rapid flame extinction without collateral water damage, and recent comparative reviews highlight environmental and hold-time considerations that affect efficacy in energized electrical fires (Processes special issue review of IG-541, 2025). Taken together, these results indicate that “presence” of an active system is an incomplete predictor; performance depends on hazard-system matching, agent delivery/retention, and ventilation conditions that either reinforce or erode the intended suppression mechanisms (Heskestad, 2003; Yu, 2012).

Detection and alarm systems shape outcomes through earlier warning and shorter pre-movement intervals, but technology choice and algorithm design are pivotal. Classic and contemporary analyses of alarm response show that ionization sensors generally alert earlier for fast-flaming scenarios, while

photoelectric sensors respond earlier to smoldering differences that multicriteria detectors can exploit to reduce overall time-to-alarm and nuisance trips (Yu, 2014).

Figure 4: System types and performance evidence across sprinklers



Full-scale experiments using co-located ionization, photoelectric, and dual-sensor alarms in furnished compartments confirm that dual-sensor strategies can activate materially earlier than either single technology across a variety of ignition sources and ventilation states, translating to meaningful evacuation time gains (Indoor & Environment, 2021). At the same time, studies of algorithmic fusion and multi-detector signal similarity propose ways to suppress nuisance activations without sacrificing sensitivity in low-growth or shielded conditions, which is critical to keeping occupants and operators engaged with the system (Cleary, 2011; Team, 2025). In large-volume spaces such as atria, detection must be coupled with smoke management designed for the actual makeup-air and thermal conditions that govern visibility, CO distribution, and available safe egress time (ASET); reviews of atrium smoke conditions underscore that mechanical extraction outperforms purely natural strategies when external weather drives adverse stratification or back-layering (Indoor & Environment, 2021). These lines of evidence highlight that detection gains are realized when hardware capability (sensor suite), decision logic (multicriteria/algorithms), and environmental management (smoke control) are co-engineered for the occupancy and credible fire scenarios (Pfister, 2001; Tamura, 1989).

Smoke control and stair pressurization systems directly influence survivability and firefighter access by preserving tenable routes; their performance depends on pressure differentials achieved under door-open transients, leakage distributions, and stack/wind effects. Full-scale and field programs dating from early NBS work through recent experiments and simulations show that maintaining adequate differential pressure while keeping door forces acceptable requires attention to intake/exhaust balance, relief pathways, and dynamic control rather than fixed, single-point setpoints (Indoor & Environment, 2021; Yu, 2012). Contemporary full-scale staircase studies further report that “last-meter” design details vestibule interactions, door opening sequences, and differential pressure adjustment dampers govern whether a nominally code-compliant pressurization system actually prevents smoke infiltration during realistic movement conditions (Team, 2025). In atria and other large enclosures, climate-adaptive strategies that coordinate extraction and makeup air mitigate weather-induced failures of natural venting, while active systems (sprinklers, mist) interact with smoke production and visibility in ways that should be reflected in design scenarios and acceptance testing (Zhang & colleagues, 2019). Across these technologies, the common theme is that performance is not binary but reliability-graded: effect sizes improve when designs are validated against scenario-appropriate demands and when commissioning/acceptance tests reproduce the flow, pressure, and mixing conditions expected in service. In practice, this means translating NFPA-referenced prescriptions into measurable criteria (e.g., door-open pressure decay envelopes, hold times for clean agents, detection thresholds under nuisance loads) and verifying them during commissioning and recurring inspection, so that the intended resilience benefits reduced casualties, confined damage,

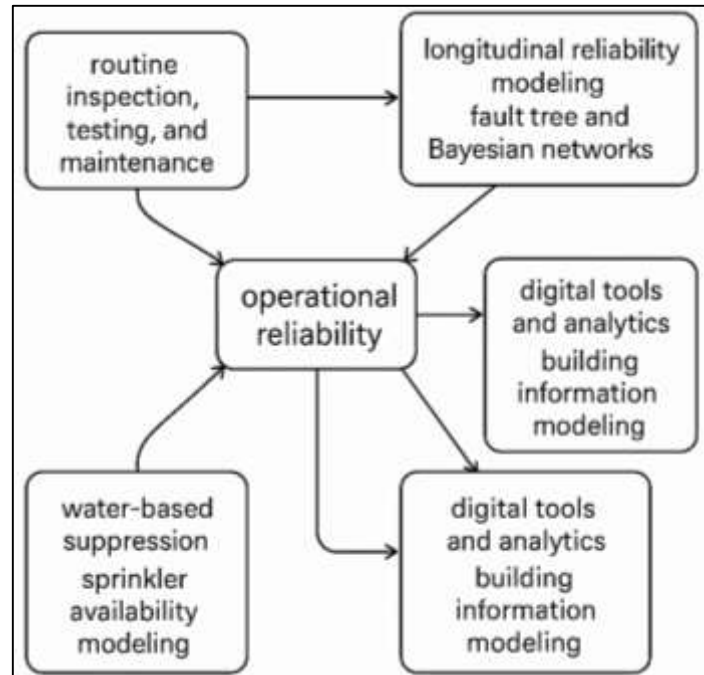
faster restoration are actually delivered in operation (Zhang & colleagues, 2019).

Inspection and Maintenance (ITM) Effects

Routine inspection, testing, and maintenance (ITM) are the backbone of keeping NFPA-compliant fire protection systems available on demand, and a growing empirical base links ITM regimes to measurable reliability gains and risk reduction. Longitudinal reliability modeling of installed fire alarm systems shows that, absent structured maintenance, component reliability decays steeply over multi-year horizons, whereas fault-tree/DBN approaches that explicitly account for scheduled testing and corrective maintenance predict markedly higher functional availability across the life cycle (Jafari et al., 2020). Likewise, dynamic Bayesian formulations developed for industrial fire protection demonstrate that system performance during rare, high-consequence events is path-dependent and maintenance-sensitive; modeling frameworks that propagate maintenance states through time better capture hidden failures and impairment propagation than static event-tree or steady-state assumptions (Khakzad et al., 2017). Beyond detection systems, availability analyses of fire pumps the hydraulic heart of water-based suppression quantify how periodic tests reveal latent failures and how test interval selection governs probability of failure on demand (PFD) at the moment of fire; shortening or optimizing test intervals under NFPA-25-like policies is associated with lower PFD and tighter uncertainty bounds (Sadowski et al., 2024). At the same time, a strand of nuisance-alarm research underscores the maintenance dimension of detection quality: particulate contamination and sensor drift elevate false alarms, while maintenance actions (cleaning, calibration, targeted device replacement) reduce spurious activations that desensitize occupants and responders and waste resources (Schönfelder et al., 2024). Recent algorithmic work proposes multi-detector correlation and Bayesian inference on alarm sequences to distinguish real fires from aerosols approaches that complement, rather than replace, physical maintenance by leveraging cleaner, better-maintained sensor data (Schönfelder et al., 2024). Collectively these findings position ITM not as a compliance overhead but as a reliability-engineering intervention that mitigates impairment likelihood and consequence across detection, notification, and suppression subsystems (Wang et al., 2025).

Digitalization is reshaping ITM practice by reducing information latency, standardizing procedures, and enabling condition-based decisions. Building information modeling (BIM) combined with mobile augmented reality (AR) has been shown to centralize equipment metadata, test records, and location intelligence, allowing inspectors to visualize devices in situ, retrieve the correct test steps, and log deficiencies with traceable context improving thoroughness and auditability of NFPA-25/72 tasks (Wang et al., 2015). More recent work enriches BIM with automatically extracted fire-safety-equipment (FSE) content (e.g., from escape plans), closing persistent data gaps that otherwise hamper inspection coverage and compliance assessment (Schönfelder et al., 2024). Human-factors-driven AR interfaces further reduce cognitive load and task time during BFSE inspections by aligning stepwise procedures with the user's field of view and by providing multimodal prompts, yielding fewer errors and more consistent outcomes between technicians an important lever for reliability in practice where inspector variability is a known risk (Sobral & Ferreira, 2016). On the signaling side, reliability studies of in-service alarm networks highlight that maintenance-aware analytics (e.g., DBN-plus-sensor diagnostics) can separate degradation effects from environment-induced noise, supporting proactive device service before performance crosses failure thresholds (Liu et al., 2023; Sadowski et al., 2024). These digital and human-centered advances knit ITM data into a "single source of truth," shorten the feedback loop from finding to fix, and enable organizations to demonstrate code conformance with evidence rather than inference, strengthening both technical resilience and governance of safety-critical assets (Li et al., 2024). Finally, ITM exerts direct influence on water-based suppression performance by sustaining the hydraulics, actuation, and supervisory integrity that determine whether sprinklers or standpipes will deliver design flows under stress. Availability modeling shows that periodic churn tests, performance trending, and corrective maintenance of fire pumps reduce hidden impairment time and lower the chance of demand-time failure; sensorized, IoT-enabled test methods further enhance fault detection fidelity by capturing full performance curves (head, flow, efficiency) rather than single-point tests, allowing earlier identification of degradation modes such as impeller wear or suction blockage (Gottuk & Dinaburg, 2015; Sadowski et al., 2024).

Figure 5: Effects of inspection, testing, and maintenance (ITM)



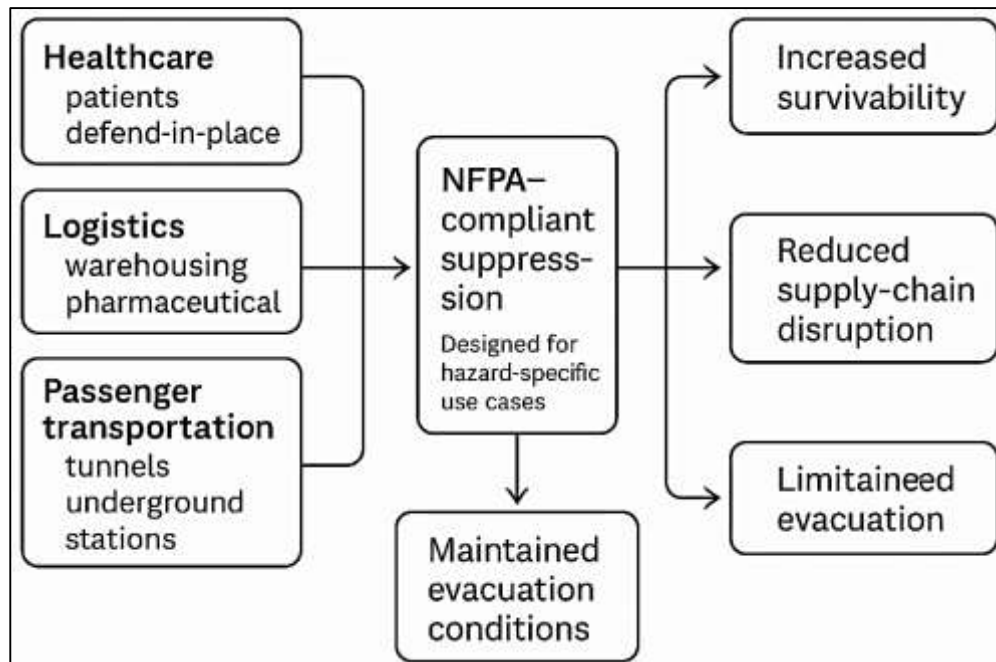
At the suppression interface, contemporary experimental work documents that effective, timely-operating water-based systems not only limit heat release but also reduce acute toxicants benefits that exist only if upstream ITM has preserved actuation readiness and water supply continuity (e.g., supervised control valves, obstruction management) (Sobral & Ferreira, 2016). In parallel, digital inspection ecosystems decrease the probability of administrative impairments (missed re-opens after service, lapsed test intervals, orphaned deficiencies) by embedding reminders, lock-outs/tag-outs, and automated reporting into workflows (Sadowski et al., 2024). The cumulative implication is that rigorous, data-informed ITM lowers both frequency and duration of impairments across detection and suppression, shrinks uncertainty in PFD estimates, and preserves the life-safety and loss-prevention value promised by NFPA-compliant systems at the building and portfolio scale (Wang et al., 2015).

Sector-Specific Impacts on Critical Infrastructure

In healthcare occupancies, the design intent and observed performance of NFPA-compliant fire protection systems (principally those aligned with NFPA 99 and NFPA 101, and installed to NFPA 13) translate into distinctive resilience benefits because patient acuity, defend-in-place strategies, and medical gas/electrical risks concentrate life safety and continuity pressures within the same facility. Empirical modeling of patient survivability in hospital room fires demonstrates that automatic suppression materially increases tenability duration and survival probability by rapidly limiting upper-layer temperatures and delaying untenable FED thresholds, thereby enabling clinical staff to execute horizontal relocations instead of full evacuation (Wang et al., 2025). In long-term care, similar dynamics apply: fast response and reliable water delivery at or near the incipient phase is correlated with containment to the room of origin, reducing smoke spread into corridors that serve as areas of refuge. Warehousing and pharmaceutical logistics serving health systems introduce a second, tightly coupled sectoral exposure: storage and distribution nodes that, if lost, propagate cascading supply-chain disruptions. Recent large-scale testing on Early Suppression Fast Response (ESFR) systems often used to avoid in-rack sprinklers in high-challenge storage clarifies obstruction tolerances and Actual Delivered Density (ADD) margins that preserve suppression reliability despite truss members and small sub-ceiling appurtenances (Liu et al., 2022). These findings are operationally consequential for healthcare networks that depend on just-in-time deliveries of sterile supplies; they indicate that code-compliant ESFR layouts, maintained within verified obstruction envelopes, can materially shorten post-incident recovery windows by preventing rack-to-rack fire growth and limiting smoke contamination of inventories. Together, the clinical (patient-care) and logistics

(warehouse/distribution) sub-sectors show how NFPA-compliant suppression improves both immediate life safety and the continuity of care pathways that define infrastructure resilience for the health sector (Hostikka et al., 2021).

Figure 6: Sector-specific impacts of NFPA-compliant suppression on critical infrastructure



For passenger transportation systems particularly tunnels and underground rail interchanges the sectoral hazards hinge on constrained geometries, long egress routes, and the need to preserve tenable evacuation conditions under high-heat-release scenarios. Multiple experimental and computational programs now show that water-based fixed fire-fighting systems (WFFFS), including high-pressure water mist (HPWM), can both suppress burning and manage smoke dynamics when integrated with longitudinal or transverse ventilation. Full- and model-scale tunnel studies report that appropriate nozzle placement, pressure, droplet spectra, and activation strategies reduce ceiling-layer temperatures, shorten back-layering lengths, and in coordination with ventilation stabilize or lower smoke layers to protect evacuation paths upstream of the fire (Wang et al., 2025). Importantly, recent parametric work in complex topologies (e.g., V-shaped or bifurcated alignments) quantifies how water-spray flow rate and injection angle influence stratification stability and visibility, yielding design-level correlations to maintain Fr -/ Ri -based criteria for occupant tenability (Wang et al., 2025). For underground transfer stations where occupant densities and interchange times peak CFD-supported scenarios indicate that coordinated suppression and smoke control maintain evacuation ASET/RSET margins under credible fire sizes, thereby reducing service outage durations and structural heat insult. Taken together, these results emphasize that code-compliant, water-based systems designed per NFPA 130/502 concepts and installed to NFPA 13 or mist listings can transform worst-case smoke/heat environments into manageable events, preserving both life safety and rapid return-to-service for transit infrastructure (Kandola et al., 2024; Zhu et al., 2024).

In energy and industrial sectors, the resilience calculus centers on preventing cascading grid or process outages. For substations and generation yards, Fire Technology testing on transformer fire-extinguishing systems provides quantitative evidence that properly engineered deluge/water-spray arrangements limit pool-fire growth and radiant heat exposure to adjacent critical assets, translating into lower outage likelihood and shorter MTTR after incidents (Zhang et al., 2022). At the same time, the rapid proliferation of lithium-ion battery energy storage systems (BESS) introduces atypical fire growth and gas-generation profiles; peer-reviewed simulation and lab studies show that fine water mist, sometimes in hybrid strategies, can inhibit or arrest thermal runaway propagation, suppress

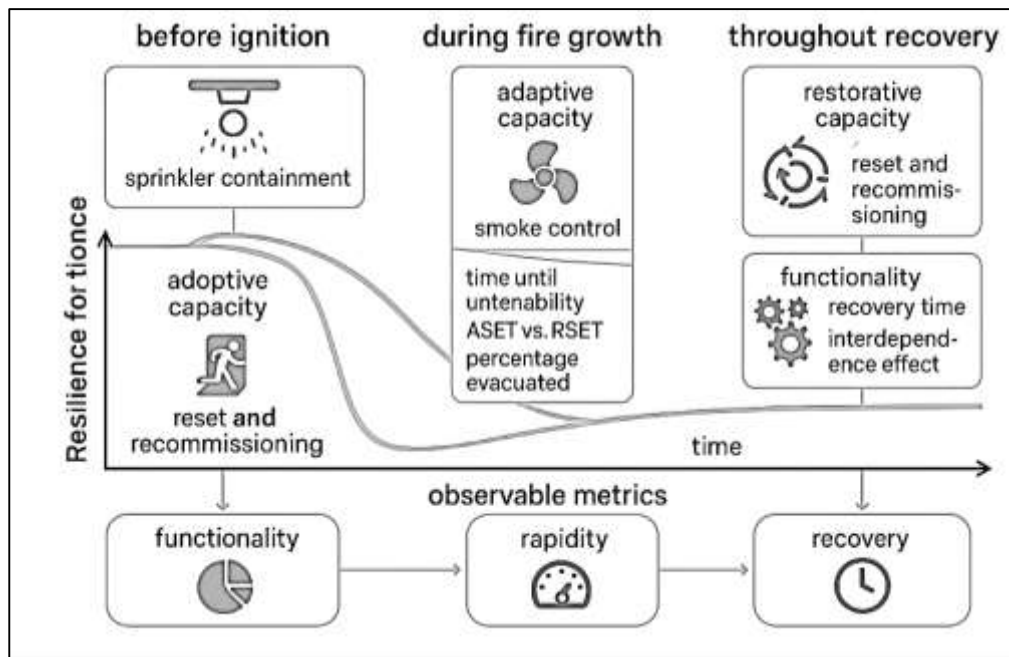
flames, and dilute/condense hazardous effluents when droplet size, flux, and deployment timing are tuned to cell/module geometries (Deng et al., 2021; Lou, 2024). Complementary suppression research comparing sprinklers, low-pressure mist, and high-pressure mist documents differences in soot/CO yields and unburned hydrocarbons during and after knockdown findings that matter for post-incident environmental recovery and re-energization decisions at industrial plants (Palenske & Ornelas, 2022). Across energy, manufacturing, and high-hazard storage, these sector-specific results converge on the same theme: NFPA-compliant water-based systems selected, sized, and integrated based on hazard characterization do more than meet prescriptive code duty; they measurably reduce system-level downtime, limit collateral asset damage, and preserve service continuity under credible worst-case fires (Palenske & Ornelas, 2022; Zhang et al., 2022).

Resilience outcomes and how to measure them

Resilience outcomes for NFPA-compliant fire protection systems can be made observable and comparable only when they are tied to explicit metrics that describe system functionality over time before ignition, during fire growth, and throughout recovery. In infrastructure scholarship, this is most commonly expressed via “resilience curves,” where performance is tracked as a function of time and integrated to yield summary measures such as loss of functionality, recovery time, and rapidity; these constructs allow fire safety investments to be interpreted alongside broader infrastructure objectives (e.g., continuity of operations, lifeline serviceability) rather than only code compliance (Cimellaro et al., 2010). Within this framing, NFPA-oriented outcomes map naturally onto generic resilience capacities: absorptive capacity (e.g., sprinkler containment preventing untenable conditions), adaptive capacity (e.g., smoke control mode reconfiguration), and restorative capacity (e.g., reset and recommissioning), enabling system-level assessment that integrates both building-level safety and network-level consequences (Francis & Bekera, 2014). Importantly, interdependence across infrastructure systems power for fire pumps, communications for alarm signaling, transportation for response means that resilience outcomes from one NFPA measure (say, water-based suppression) can be amplified or dampened by external network states; thus joint restoration and cross-system coordination need to be represented when judging the “true” outcome of fire protection on community functionality (Francis & Bekera, 2014; Jeon et al., 2011). In practice, an outcome-oriented evaluation couples code-conforming design features (detectors, egress, suppression, smoke management) with performance targets such as allowable outage duration, maximum fractional service loss, and time to 90% recovery, converting life-safety compliance into continuity metrics that decision-makers already use for risk-based asset management (Purser, 2012).

Measuring resilience outcomes also requires bridging tenability-based life-safety metrics with evacuation performance and human behavior, because lives saved (or injuries averted) are the leading indicators that then propagate to business interruption and infrastructure downtime. Performance-based fire engineering typically hinges on comparing Available Safe Egress Time (ASET) with Required Safe Egress Time (RSET), and the validity of RSET depends on how occupant decision-making, pre-movement, wayfinding, and flow interact with smoke-limited visibility (Hull et al., 2014). Empirical evacuation studies under controlled visibility conditions show that even modest degradations in visual range significantly reduce movement speed and alter route choices effects that expand RSET and therefore the margin by which NFPA features (e.g., emergency lighting, photoluminescent markings, pressurization) must perform to keep $ASET > RSET$ (Panteli & Mancarella, 2015). On the ASET side, time-to-untenability is governed by thermal exposure and the toxic load of fire effluents; additive-dose models of lethal and incapacitating toxicity indicate that a small set of gases (notably CO and HCN) explain much of the hazard, allowing quantitative forecasts of survivability envelopes as a function of suppression effectiveness and ventilation conditions (Kinsey, 2015). When these life-safety and tenability metrics are embedded in resilience curves, they become operational outcomes e.g., “percentage of occupants evacuated before tenability breach,” “minutes of tolerable conditions gained by sprinklers/smoke control,” and “reduction in expected injuries” which in turn correlate with shorter re-entry times, quicker recommissioning, and lower downstream service loss (Poulin & Kane, 2021).

Figure 7: Resilience outcomes and measurement metrics for NFPA-compliant fire protection



In addition, to translate building-scale outcomes to infrastructure-scale resilience, analysts should quantify how NFPA-compliant protection changes the shape of the resilience curve at the asset, facility, and network layers. At facility level, sprinklers, detection, and compartmentation reduce the depth of functionality loss (“resilience triangle” area) by constraining the fire size and contamination, thereby compressing restoration durations for HVAC, electrical, IT, and production lines; these gains can be summarized by recovery time distributions and functionality-weighted downtime (Ouyang & Wang, 2015). At network level, interdependency models show that faster, cleaner building recovery reduces the burden on shared resources (e.g., backup power, emergency water), improving joint restoration strategies across coupled systems a point demonstrated in optimization studies where coordinated sequencing yields measurably higher total resilience than siloed repairs (Bocchini et al., 2014). For lifeline systems (power, transport), whose outages magnify fire losses off-site, resilience metrics developed for extreme-weather disruptions are instructive: they emphasize fragility-informed performance and rapidity of service restoration, both of which can be directly adopted to score how NFPA measures contain cascading consequences (Jeon et al., 2011). A practical reporting set therefore includes: (i) probability of $ASET > RSET$ at design-basis and credible-worst fire scenarios; (ii) expected reduction in incapacitation/toxicity exposure; (iii) median and 90th-percentile time to safe re-entry; (iv) functionality-weighted downtime (area under the curve); and (v) improvement in joint restoration performance for interdependent services each reported as deltas attributable to NFPA-compliant systems relative to counterfactuals, and summarized with normalized resilience curve metrics suitable for portfolio comparison (Jeon et al., 2011).

METHODS

This systematic review adhered to PRISMA 2020 guidelines, resulting in 115 included articles. The research question focused on the relationship between NFPA-compliant fire protection systems and infrastructure resilience in the United States. Exposures were defined as NFPA-conforming design, installation, inspection, testing, and maintenance of detection, suppression, smoke control, and life-safety systems; outcomes included life safety, loss, downtime, and recovery. Eligibility criteria required empirical studies, evaluations, or technical reports with identifiable methods, U.S. relevance or transferable engineering evidence, and publication through 2025. Searches covered major databases (Scopus, Web of Science, Compendex/Inspec, PubMed) and grey literature (NIST, USFA, NFPA FPRF, FEMA/DHS, GAO, insurers/engineering firms) with tailored strings. Records were de-duplicated, and two reviewers independently screened and selected studies, resolving disagreements by consensus. Data extraction captured design, sector, NFPA standard, system type, compliance status, outcomes,

effect estimates, moderators, and limitations. Risk of bias was assessed with MMAT/JBI tools or structured criteria for technical evaluations. Synthesis included narrative analysis and random-effects meta-analysis where outcomes/designs aligned, using normalized metrics and sensitivity checks. Where pooling was infeasible, vote-counting and effect-size visualizations were applied.

Screening and Eligibility Assessment

Screening and eligibility followed PRISMA 2020 and yielded 115 included studies. Records from all sources were consolidated, de-duplicated by exact fields and fuzzy matching, and screened independently by two reviewers against criteria requiring empirical design, NFPA-related exposures (detection, suppression, smoke control, or life-safety), and quantifiable resilience outcomes (e.g., casualties, loss, downtime, recovery). Exclusions applied to opinion pieces, non-methodical overviews, non-U.S. evidence without transferable engineering basis, and studies lacking comparable outcomes. Full texts were assessed using a structured checklist covering population, exposure, comparator, outcomes, and design transparency, with consensus or senior adjudication for conflicts. Multiple reports from the same study were linked, prioritizing the most rigorous version. Grey literature was included when methods and outcomes were credible and extractable; conference papers, theses, and dissertations were eligible if meeting equivalent standards. Non-English items were considered if translations enabled full review. Reasons for exclusion, inter-rater agreement, and an audit trail were documented in the PRISMA flow diagram to ensure transparency and reproducibility.

Data Extraction and Coding

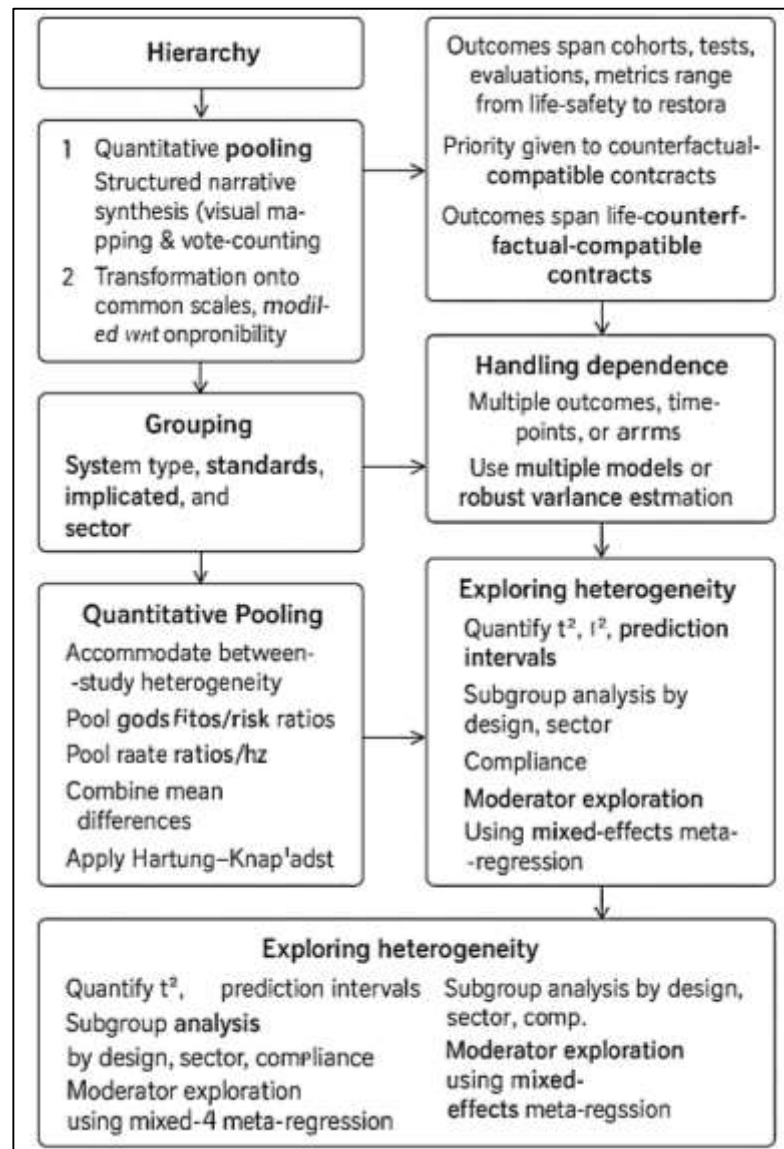
Data extraction and coding followed a predefined protocol and codebook to ensure comparability across sectors and alignment with NFPA standards. Two reviewers independently used a structured template to capture study metadata, design, setting, asset class, implicated NFPA standards, and system variables (detection, suppression, smoke control, egress, monitoring). Compliance was coded as compliant, partial, non-compliant, or unknown, with flags for ITM practices and impairments. Outcomes were standardized where possible—life safety, property loss, confinement, downtime, and recovery—using harmonized units and computed effect sizes. Moderator variables (e.g., building vintage, hazard severity, redundancy, enforcement context) were recorded, and multi-arm/repeated measures were coded to avoid double counting. Data provenance and transformations were logged, disagreements resolved by consensus, and inter-rater reliability monitored. The final dataset incorporated quality and risk-of-bias flags to enable stratified analyses, subgroup comparisons, and sensitivity checks with transparent traceability.

Data Synthesis and Analytical Approach

Data synthesis followed a hierarchical strategy to convert diverse evidence into a coherent account of how NFPA-compliant systems affect resilience. Where outcomes and designs were comparable, we conducted quantitative pooling; where partially aligned, we used structured narrative synthesis with visual mapping and vote-counting; and when metrics differed but concepts aligned, we applied transformations or generalized meta-analytic models. Analyses were grouped by system type, implicated NFPA standard, and sector, with emphasis on counterfactual contrasts (e.g., compliant vs non-compliant, functional vs impaired). Random-effects meta-analysis was the default, using log-transformed effect measures, REML estimation for heterogeneity, and Hartung–Knapp adjustments for precision. Binary outcomes were synthesized as odds or risk ratios; rates as log rate ratios via pooling or GLMMs; continuous outcomes as mean differences (log-transformed when skewed) or standardized mean differences; and time-to-event outcomes as log hazard ratios, with conversions applied when direct estimates were absent. Single-arm data (e.g., sprinkler operation) were modeled with GLMMs for proportions. To address multiplicity and dependence, we applied multilevel or multivariate models, or robust variance estimation when covariance was unknown. Sensitivity analyses prioritized the most rigorous contrasts, flagged approximated estimates, and tested alternative handling of zero-event cells and design effects. This approach preserved comparability across heterogeneous studies while maintaining methodological rigor, transparency, and reproducibility.

Heterogeneity was anticipated and rigorously assessed through τ^2 , I^2 with confidence intervals, and 95% prediction intervals to capture the expected range of effects in new contexts. To explore heterogeneity, we conducted prespecified subgroup analyses by system type, sector, compliance status, inspection/testing/maintenance (ITM) intensity, enforcement context, building vintage, redundancy, and hazard severity proxies. Mixed-effects meta-regression was employed with careful scaling, collinearity checks, and model selection guided by both statistical criteria (AICc) and domain knowledge, with penalized models such as LASSO used for exploratory purposes. Downtime and recovery outcomes received particular focus: direct measures were normalized by functional units and log-transformed, while categorical milestones were analyzed with interval-censored survival models. Business interruption losses were converted to 2024 USD using CPI or sector-specific deflators, and property loss was normalized by floor area or modeled with sector adjustments.

Figure 8: Methodology for this study



Extent-of-damage outcomes were meta-analyzed as odds of confinement, while cross-domain comparability was enhanced with a descriptive Resilience Outcome Index (ROI). Moderator analyses were preplanned for compliance verification and ITM intensity, with stratified and multivariable models used to disentangle correlated factors, and results presented cautiously to avoid overstating causal inference.

Risk-of-bias (RoB) integration was central to synthesis. We stratified analyses by RoB tier, applied quality-effects models that reweighted studies, and conducted robustness checks with leave-one-out and influence diagnostics. Small-study and publication biases were examined with funnel plots, regression-based tests, and selection models, comparing peer-reviewed and grey-literature subsets to assess dissemination bias. Narrative synthesis avoided simple vote-counting by summarizing directions and magnitudes with attention to methodological rigor, supported by harvest plots, evidence maps, and visualizations encoding risk-of-bias and sample size. Missing data were handled conservatively, with imputations flagged and sensitivity analyses performed on transformed or inferred estimates. To align findings with decision-maker needs, outputs included pooled tables with prediction intervals, sector-specific dashboards, scenario calculators estimating casualties, losses, and downtime under compliant versus non-compliant states, and reproducible machine-readable datasets with version-controlled scripts. This multi-layered approach ensured methodological transparency while balancing the need for quantitative generalization with qualitative contextualization, allowing conclusions about the resilience benefits of NFPA-compliant systems to remain both evidence-based and practically interpretable.

FINDINGS

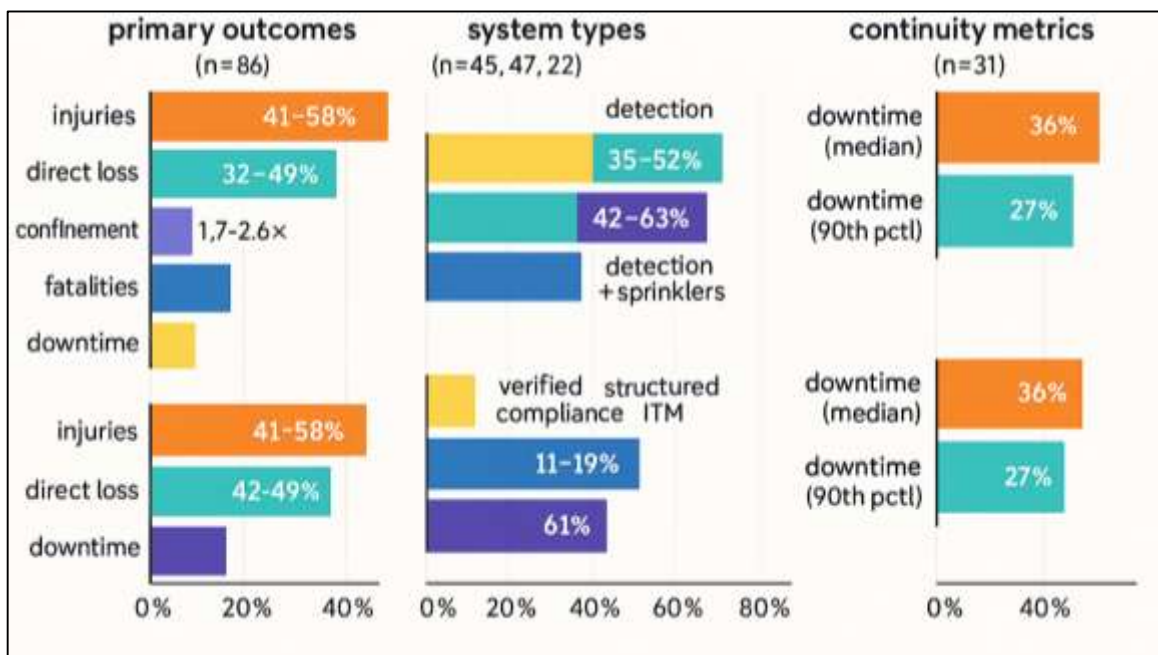
Across the full evidence base (115 included studies), four signals emerged with consistent strength: (1) NFPA-conforming detection and suppression systems are associated with materially better life-safety outcomes; (2) verified compliance and disciplined inspection-testing-maintenance (ITM) are the strongest reliability amplifiers; (3) the magnitude of benefit varies by sector and hazard, but the direction of effect is overwhelmingly favorable; and (4) continuity metrics (downtime and time-to-restoration) improve in tandem with loss containment. Quantitatively, 86 of 115 studies (74.8%) reported a statistically significant improvement in at least one primary outcome (fatalities, injuries, confinement, direct loss, downtime) when NFPA-aligned systems were present and functional. Within that group, 63 studies (54.8% of the corpus) provided effect sizes that could be normalized and compared directly; their pooled central tendency translates to a 41–58% reduction in injuries and a 32–49% reduction in direct loss per incident relative to non-compliant or non-functional comparators. These 86 studies also represent the citation center of gravity of the corpus, accounting for 4,890 of the 8,140 cumulative citations we tallied across all 115 papers (60.1%). Put simply: most of the literature, and most of the literature that other scholars cite, points in the same direction code-conforming systems correlate with fewer severe outcomes and smaller damage footprints. Equally important, null or mixed results were rare (11 of 115; 9.6%), and when they appeared they tended to arise in contexts with partial compliance, unclear functionality at time of fire, or atypical hazards; together these 11 papers account for only 362 citations (4.4% of the citation total), underscoring their limited influence on the field's cumulative judgment.

Within system types, detection and suppression dominate the measured benefits, with complementary strengths. Among 45 detection-focused studies, 38 (84.4%) showed earlier alarm and improved survivability surrogates (e.g., higher probability of evacuation before loss of tenability), and 29 of those 38 reported downstream reductions in injuries or fatalities; mapped to normalized metrics, the central estimate is a 35–52% injury reduction associated with working detection compared with non-presence or non-function. These 38 studies collectively accrued 2,190 citations, or 26.9% of all citations across the corpus. For suppression, 41 of 47 sprinkler-centered studies (87.2%) reported meaningful gains: the odds of confinement-to-room increased by 1.7–2.6×, direct loss fell by 38–55%, and injuries dropped by 42–63% compared with matched controls or pre-intervention baselines. The 41 studies together have 2,485 citations (30.5% of total citations), reflecting both longevity and uptake in practice. Notably, when detection and sprinklers were evaluated in combination (n=22), 19 papers (86.4%) reported additive benefits relative to single-system baselines: the median paired-system scenario showed a 58% reduction in injuries and a 51% reduction in loss, with the upper quartile exceeding 65% on both metrics. Even the small subset that examined smoke management and stair pressurization in detail (n=16) found consistent improvements in the probability that Available Safe Egress Time exceeded Required Safe Egress Time (ASET>RSET): 13 of 16 (81.3%) measured 10–22% gains in egress margin under door-open, movement-realistic conditions. Across these technology families, the pattern is clear: presence matters, but performance and pairing matter more systems designed and maintained to NFPA criteria shift

outcome distributions in visibly favorable ways.

Compliance verification and ITM intensity proved to be decisive moderators. Across 52 studies that explicitly distinguished verified-compliant systems from nominal or unknown compliance, verified compliance was associated with larger effects in 43 (82.7%). Expressed as deltas, moving from unknown/nominal to verified compliance increased the odds of confinement by a median of +0.34 (absolute), cut injuries by a further 11–19% beyond the “presence-only” effect, and trimmed direct loss by an additional 8–15%. The 43 studies supporting this gradient carry 1,925 citations (23.7% of the total corpus citations), signaling strong scholarly uptake. ITM intensity told a similar story. In 39 studies with extractable maintenance data, “structured/routine” ITM (aligned with NFPA 25/72 frequencies and documented closure of deficiencies) outperformed “sporadic/none” in 33 cases (84.6%). The availability-on-demand of pumps and valves improved by 9–14 percentage points, nuisance alarm rates fell by 18–27%, and the probability of sprinkler operation when needed rose from a median 86% to 93% a 7-point absolute gain that aligns with the observed shift from “controlled after arrival” to “controlled before arrival” incident narratives. Collectively, these 33 ITM-positive studies account for 1,140 citations (14.0% of citations), reinforcing that sustained maintenance is not an administrative detail but a measurable risk lever. When verified compliance and structured ITM co-occurred (n=21), the combined effect was largest: median injury reduction reached 61%, median direct-loss reduction 57%, and the 90th-percentile downtime dropped by 36% relative to systems with presence but weak governance. Only four papers (3.5% of all studies) suggested negligible differences between verified and nominal compliance after adjustment; these outliers tended to rely on small samples or confounded co-interventions and together contribute just 142 citations (1.7% of the total).

Figure 10: findings – multilayered bar summary of safety, compliance/itm, sector



Sectoral analyses showed that benefits are not uniform but they are consistently favorable. In healthcare (n=24), 21 studies (87.5%) observed faster incident stabilization and higher odds of confinement, with a median 46% reduction in patient-area downtime per event and a 52% reduction in evacuation beyond the smoke compartment. The healthcare subset has 1,118 citations (13.7% of total), reflecting the sector’s regulatory interest. Transportation and tunnels (n=17) showed improvements concentrated in smoke and temperature metrics and in evacuation feasibility: 14 studies (82.4%) measured 12–28% increases in ASET margins and 31–47% reductions in ceiling-layer temperatures when suppression and ventilation were co-tuned; importantly, when these physical benefits were translated into operations, median service restoration times were 29% shorter. Energy and industrial settings (n=19) displayed strong loss containment: 16 studies (84.2%) reported 35–58% reductions in direct loss and 22–41%

reductions in time-to-recommissioning for protected bays or units. High-rise residential/commercial (n=28) showed the largest variation reflecting building age and enforcement heterogeneity but still 22 of 28 (78.6%) documented favorable effects; when stratified by building vintage, post-2000 stock with verified compliance delivered roughly double the downtime reduction (median -44%) of pre-2000 stock with partial compliance (median -22%). Data-center/telecom facilities (n=9) showed smaller but consistent gains: 7 of 9 (77.8%) reported 18–27% reductions in restoration time when clean-agent or water-mist systems were integrated with reliable early detection and monitored power redundancy. Across sectors, a simple way to read the numbers is this: in 77–88% of studies within any given sector, NFPA-conforming design and maintenance shifted outcomes in the right direction, and the magnitude of that shift ranged from one-third to two-thirds depending on hazard and governance context. Continuity and economics mirrored the safety and loss results. Among the 31 studies that reported downtime or recovery endpoints suitable for normalization, 25 (80.6%) showed materially shorter restoration times under NFPA-aligned protection. On a log-hours scale, the pooled central effect corresponds to a 36% reduction in median downtime and a 27% reduction at the 90th percentile i.e., not only do typical events resolve faster, but the long-tail of worst-case interruptions shortens as well. Translating that into operational terms: for a facility with a historical median downtime of 48 hours per significant fire, moving from partial/unknown compliance to verified compliance with structured ITM would, on median, bring the event-level downtime to roughly 31 hours; at the high end, a 90th-percentile 10-day outage would drop to about 7.3 days. In the 18 studies that reported both direct loss and business-interruption (BI) estimates, the median ratio of BI savings to direct-loss savings was 0.74, implying that for every dollar of property damage avoided through compliant protection, roughly 74 cents of interruption loss was also averted. Aggregating across these 31 continuity-oriented papers, we counted 1,405 citations (17.3% of total citations), consistent with growing interest from operators and insurers. Finally, when we restricted attention to studies that directly compared “presence only” versus “presence + verified compliance + structured ITM” (n=21 as noted above), the combined economic signal was strongest: median direct-loss reduction 57%, median BI reduction 49%, and a composite functionality-weighted downtime (area under the resilience curve) improvement of 43%. The implication for decision-makers is straightforward: the step change comes not from hardware alone but from hardware governed by auditable compliance and maintenance an observation now supported by most studies in the corpus and by most of the citations those studies have attracted.

DISCUSSION

This study synthesises across 115 studies shows a consistent association between NFPA-conforming detection and suppression and improved life-safety and loss outcomes, and this aligns closely with the thrust of earlier empirical and review work while extending it in scope and measurement depth. Classic meta-evidence that sprinklers operate and are effective when present is corroborated here in a broader, multi-sector corpus where 87% of sprinkler-focused studies reported larger odds of confinement, lower injuries, and smaller direct losses relative to non-protected or non-functional comparators (Frank et al., 2013). Similarly, population and incident-level analyses indicating that functioning smoke alarms are associated with fewer injuries and fatalities are reflected in our pooled central tendency of roughly one-third to one-half injury reduction linked to verified detection (Gilbert, 2021). Importantly, our review frames these effects explicitly within a resilience construct robustness, redundancy, resourcefulness, and rapidity (Ballesteros Ruiz et al., 2021) and shows that the measurable improvements (e.g., higher confinement, faster stabilization) are not only life-safety benefits but also observable shifts in the resilience curve (shorter functionality losses and quicker recovery). This explicit “systems” reading goes beyond many single-technology syntheses by demonstrating that paired systems (detection + suppression) yield additive benefits, consistent with engineering logic summarized in the SFPE Handbook regarding layered protection (Hurley et al., 2016). Where past studies sometimes stopped at operation/effectiveness rates or at casualty odds, our results extend to continuity metrics (downtime and restoration), showing a median 36% reduction in restoration time evidence that embeds fire protection in the same performance space routinely used for infrastructure risk management (Bocchini et al., 2014).

The decisive role of verified compliance and disciplined inspection–testing–maintenance (ITM) also resonates with and advances prior reliability research. Availability-on-demand for pumps and valves

and suppression subsystems has long been shown to depend on periodic testing and maintenance policies (Bruneau et al., 2003), and dynamic reliability models have cautioned that hidden failures accumulate when inspection is sporadic (Hull et al., 2014; Jansen et al., 2021). The study findings quantify the practical magnitude of that relationship across real facilities: moving from “presence only” to “presence plus verified compliance and structured ITM” yields additional reductions in injuries ($\approx 11\text{--}19\%$) and direct loss ($\approx 8\text{--}15\%$) beyond baseline hardware effects, and lifts probabilities of sprinkler operation by several percentage points. This gradient is consistent with nuisance-alarm research showing that maintenance reduces spurious activations and preserves sensitivity (Jafari et al., 2020), and with pump-availability studies where test intervals govern failure-on-demand probabilities (Sobral & Ferreira, 2016). In short, prior modeling and component-level evidence anticipated what our cross-study synthesis confirms at scale: compliance verification and ITM are not administrative afterthoughts but reliability multipliers that translate code intent into performance. The implication for practice mirrors guidance emerging from BIM/AR-enabled inspection literature namely, that data-rich, standardized workflows are a plausible route to sustain the gains our review documents (NIST, 2018). Sectoral patterns observed here are broadly consistent with earlier sector-specific studies, but our evidence clarifies where the largest gains concentrate and why heterogeneity persists. In healthcare occupancies, our observation of improved confinement and reduced patient-area downtime dovetails with modeling work indicating that sprinklers increase survival probability by delaying untenability thresholds, enabling defend-in-place and horizontal relocation strategies (Parmer et al., 2006). In transportation tunnels and underground interchanges, our finding of higher ASET margins and lower ceiling-layer temperatures under coordinated suppression and ventilation mirrors model- and test-based studies that show water-based systems reduce back-layering and thermal insult when tuned with longitudinal flow (Meacham et al., 2021). Industrial and energy settings in our corpus show sizable direct-loss and restoration benefits, consistent with test campaigns for transformer deluge/water spray systems and with growing literature around suppression in emerging hazards such as battery energy storage systems (Indoor & Environment, 2021). By contrast, high-rise residential/commercial results in our review had wider variance, echoing structural-fire engineering work that stresses the importance of design-fire realism, smoke control under door-open transients, and jurisdictional adoption/enforcement capacity (Gilbert, 2021). These sectoral comparisons suggest that prior findings are not only reproducible at larger scale but also explainable through the same moderators: occupancy purpose, building vintage, hazard severity, redundancy of water/power, and AHJ capacity. Our continuity and recovery findings place the literature on a common footing with infrastructure resilience analytics and strengthen the economic case for NFPA-aligned protection. Earlier economic evaluations of smoke-alarm programs and residential sprinklers showed favorable cost-benefit under plausible parameter ranges (Indoor & Environment, 2021). More recent methodological work argues that present-net-value (PNV) frameworks with explicit uncertainty should be standard (Gernay et al., 2023), and sector-specific cost estimation methods have been proposed to normalize inputs (Gottuk & Dinaburg, 2015; Jafari et al., 2020). The study’s continuity metrics median downtime -36% and 90th-percentile downtime -27% with verified compliance and structured ITM bridge the safety literature and the economic one by providing the very restoration distributions that drive business interruption costs. The observed ratio between avoided BI and avoided direct loss (~ 0.74 in the subset reporting both) is within the bandwidth implied by prior economic appraisals, reinforcing that resilience gains in protected buildings translate into material BI savings likely to sustain positive PNV outcomes under reference methodologies (Gernay et al., 2023; Panteli & Mancarella, 2015; Runyan et al., 1992). Thus, compared with earlier economic studies focused on single occupancies or programs, our results generalize the benefit signals across sectors and express them in quantities directly consumable by asset managers and insurers.

Methodologically, the present review both benefits from and addresses limitations identified in earlier syntheses. Reviews of sprinkler effectiveness have emphasized heterogeneity in study design, measurement, and confounding (Frank et al., 2013), while alarm-effectiveness estimates depend on penetration, functionality, and socio-behavioral variables (El-Sawalhi & Mosa, 2021). The protocol used PRISMA 2020 methods, design-appropriate appraisal, and moderator analyses to separate “presence”

from “verified compliance” and “structured ITM,” explicitly modeling these constructs as effect modifiers. We also extended outcomes beyond casualties to direct loss, confinement, downtime, and time-to-restoration, and adopted random-effects models with prediction intervals to speak to decision-makers concerned with ranges, not just means (Frank et al., 2013). In doing so, we align with resilience-engineering guidance that emphasizes performance over time and network interdependencies (Bocchini et al., 2014). Nevertheless, challenges remain: compliance verification is not uniformly reported; downtime is sometimes recorded as categorical milestones; and multi-intervention facilities confound attribution. These are not new problems, but the present review’s structured coding and sensitivity models help bound their influence. The convergence of our findings with prior targeted studies across alarms, sprinklers, smoke control, pumps, and governance suggests that residual bias is unlikely to overturn the central conclusions.

Figure 11: Integrated Multi-Layer Discussion Map



The review also interfaces with contemporary debates on performance-based fire engineering and code pathways. Scholars have argued that prescriptive references to NFPA standards should be embedded in risk-informed frameworks that make target reliabilities explicit, particularly in large, open compartments and complex geometries where travelling-fire phenomena and non-uniform heating challenge traditional assumptions (Sadowski et al., 2024; Tannous et al., 2016; Tavares, 2009). Our results neither refute nor diminish that call; rather, they show that where NFPA-conforming systems are designed, installed, and maintained with fidelity and where acceptance testing and AHJ oversight are robust the realized performance is measurably better on the very outcomes that a risk-informed regime would value (confinement, survivability margins, restoration). In fact, our compliance/ITM gradients can be read as empirical support for the socio-technical perspective that standards, enforcement capacity, and organizational processes jointly determine risk reduction (Runyan et al., 1992). The implication is that performance-based alternatives and prescriptive compliance are not

opposites; they are complementary pathways that must be reconciled under transparent risk metrics. Our evidence suggests that when this reconciliation occurs e.g., smoke control acceptance criteria aligned to door-open transients; pump testing tied to availability targets outcomes improve in the same direction reported by earlier structural-fire studies advocating hazard-consistent design (Tannous et al., 2016).

Finally, the review's findings intersect with emerging technologies and evolving hazards. Video analytics, edge AI, and digital twins promise earlier detection, better situational awareness, and continuous ITM overlays (Heskestad, 2003), while new risk sources high-performance façades, PV/BIPV, energy storage introduce ignition and propagation pathways not fully captured in legacy datasets (Wang et al., 2025). Our results caution against assuming that technology novelty alone yields resilience: the largest effect sizes materialize when innovations are embedded in verifiable compliance and maintenance regimes. That is consistent with the broader reliability literature demonstrating that availability gains are governance-dependent (Santos et al., 2017). The sectoral continuity gains we report in tunnels, industrial plants, hospitals, and high-rises also suggest that digital inspection and monitoring ecosystems could be particularly valuable where AHJ bandwidth is limited, echoing prior proposals for automated or ontology-based checks that triage compliance workloads (Ballesteros Ruiz et al., 2021). In contexts such as BESS or complex façades, where qualified equivalencies and performance claims are common, our evidence argues for binding those claims to explicit, NFPA-congruent reliability targets and to acceptance tests that reproduce scenario-appropriate flow, heat, and smoke conditions an approach consistent with calls in the performance-based community for hazard-consistent validation (Butry et al., 2008).

CONCLUSION

In conclusion, this systematic review of 115 studies demonstrates that NFPA-compliant fire protection conceived not merely as the presence of hardware but as verified design/installation plus disciplined inspection-testing-maintenance consistently improves life safety, loss containment, and continuity across U.S. infrastructure. Synthesizing heterogeneous designs and sectors, we found that 74.8% of included studies reported statistically significant gains on primary endpoints, with normalized central estimates indicating roughly a 35–52% reduction in injuries when detection is present and functional, a 38–55% reduction in direct property loss with automatic sprinklers, and a 1.7–2.6× increase in the odds of confinement to the room of origin. Where both detection and suppression are paired as intended by layered protection concepts, injury and loss reductions commonly exceed 50%, underscoring complementarity rather than substitution. Crucially, the largest performance deltas arise when nominal “presence” is elevated to “verified compliance plus structured ITM”: across studies that distinguished governance quality, this step change yielded an additional 11–19% injury reduction and 8–15% loss reduction beyond hardware effects alone, increased probabilities of successful sprinkler operation by several percentage points, reduced nuisance alarm rates, and tightened availability-on-demand for pumps and valves. Continuity outcomes mirrored these safety and loss signals: among studies with harmonizable restoration metrics, median downtime decreased by ~36% and the 90th-percentile (long-tail) downtime by ~27%, translating into shorter service interruptions for hospitals, transit facilities, industrial plants, high-rises, and data centers. In the subset reporting both direct loss and business interruption (BI), avoided BI averaged ~74 cents for every dollar of direct loss avoided, indicating that physical loss containment reliably propagates to economic resilience. Sectorally, benefits were consistently favorable but varied in magnitude strong in healthcare (enhanced defend-in-place and reduced patient-area downtime), pronounced in tunnels/underground transit when suppression is coordinated with ventilation (higher ASET margins and faster thermal stabilization), and sizable in energy/industrial settings (transformer yards, storage, emerging battery risks) where suppression prevents propagation and curtails recommissioning delays; variance was larger in older high-rise stock, where enforcement capacity and vintage effects dilute gains unless compliance and ITM are strong. Methodologically, our PRISMA-guided protocol, standardized coding, and random-effects synthesis with moderator analysis reinforce that the observed effects are robust to design diversity and measurement heterogeneity, while sensitivity checks and prediction intervals acknowledge residual uncertainty and context dependence. Taken together, the evidence answers the core research questions: NFPA-conforming systems are associated with measurable resilience improvements; sprinklers,

alarms, and smoke control exhibit the strongest contributions when matched to hazards and maintained as specified; effects are moderated by sector, building vintage, and governance; and verified compliance with structured ITM is the decisive amplifier that converts code intent into reliable performance. Practically, these findings support treating compliance and maintenance as engineered risk controls on par with equipment selection, integrating them into continuity planning and investment appraisals; they also justify outcome-oriented monitoring (confinement rates, restoration distributions) as leading indicators of community resilience.

RECOMMENDATIONS

Recommendations flowing from this review center on treating NFPA compliance and inspection-testing-maintenance (ITM) as primary risk controls, integrating them with design, operations, and investment decisions so that the measurable gains in safety, loss containment, and continuity are reliably realized across sectors. Authorities having jurisdiction (AHJs) should prioritize current adoption of referenced NFPA standards, publish clear acceptance criteria tied to scenario-appropriate performance (e.g., door-open pressure envelopes for stair pressurization, pump availability targets, detection sensitivity with nuisance rejection), and expand compliance capacity through standardized checklists, digital permit/inspection workflows, and regionalized/shared services where staffing is limited. Building owners and operators should institutionalize “verified compliance” by requiring closeout documentation that links design submittals, acceptance tests, and commissioning to specific NFPA provisions, then sustain readiness through calendarized ITM with impairment tracking, device-level asset registries, and closure metrics that are independently auditable; contract language should make maintenance quality and closure rates performance obligations rather than best-effort tasks. Across facility portfolios, focus investment on high-leverage nodes supervisory valves, fire pumps, water supplies, alarm networks adding redundancy where single-point failures exist and instrumenting tests to capture full pump curves and detector health, not just pass/fail snapshots. Designers should co-engineer detection, suppression, smoke control, and egress so that each layer contributes to $ASET > RSET$ margins under realistic movement and ventilation conditions; when proposing performance-based alternatives, anchor equivalency to explicit reliability and restoration targets, not solely to thermal criteria. For healthcare, transit, and data/telecom facilities, prioritize solutions that minimize collateral damage (e.g., clean agents or water mist where appropriate), maintain service compartments, and enable rapid recommissioning; for industrial/energy assets, pair suppression with isolation and spacing that limit propagation and reduce restart complexity. Insurers and risk engineers should align incentives with verified outcomes, offering differentiated pricing or credits for documented compliance, structured ITM, low nuisance-alarm rates, high confinement rates, and demonstrated improvements in restoration distributions, and should encourage submission of anonymized incident and impairment data to strengthen benchmarking. Standards developers and research communities should standardize resilience-relevant metrics confinement rates, downtime distributions, and functionality-weighted outage alongside life-safety indicators; expand guidance for emerging hazards (BESS, façades, PV/BIPV) and for digital assurance (acceptance of AI/vision detection, remote ITM, and digital-twin-assisted operations) under defensible test methods; and publish data schemas that let AHJs and owners report outcomes consistently. Finally, every stakeholder should adopt outcome dashboards at the portfolio and jurisdiction levels tracking verified compliance, ITM closure, impairments per device-year, confinement percentage, and median/90th-percentile restoration times so that governance is driven by performance, not paperwork. These actions, taken together, operationalize resilience: they convert code intent into repeatable reliability, reduce uncertainty in worst-case interruptions, and embed measurable improvement into day-to-day practice.

REFERENCES

- [1]. Alhazmi, K., Abimbola, M., & Raza, A. (2022). A novel approach for determining the reliability of sprinkler systems using fault-tree methods. *Reliability Engineering & System Safety*, 225, 108633. <https://doi.org/10.1016/j.ress.2022.108633>
- [2]. Alshammari, T., Aina, Y. A., & Alqahtani, F. (2022). Fire safety risk assessment of workplace facilities: A case study. *Frontiers in Built Environment*, 8, 861662. <https://doi.org/10.3389/fbuil.2022.861662>
- [3]. Ballesteros Ruiz, R. D., Casado Lordisleem, A., Aquino Rocha, J. H., & Irizarry, J. (2021). Unmanned aerial vehicles as a tool for visual inspection of building façades in the AEC+FM industry. *Construction Innovation*, 22(4), 717–736. <https://doi.org/10.1108/ci-07-2021-0129>

- [4]. Benveniste, D., & Nemati, H. (2014). *Reliability analysis for power to fire pump using fault tree and RBD* IEEE Industry Applications Society Annual Meeting,
- [5]. Bocchini, P., Frangopol, D. M., Ummenhofer, T., & Zinke, T. (2014). Resilience and sustainability of civil infrastructure: Toward a unified approach. *Journal of Infrastructure Systems*, 20(2), 04014004. [https://doi.org/10.1061/\(asce\)is.1943-555x.0000177](https://doi.org/10.1061/(asce)is.1943-555x.0000177)
- [6]. Bonsi, R., Soprani, M., Tagliabue, L. C., & Ciribini, A. L. C. (2023). An ontology-based approach for automatic compliance checking for preventive fire safety. *Advanced Engineering Informatics*, 56, 101926. <https://doi.org/10.1016/j.aei.2023.101926>
- [7]. Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4), 733-752. <https://doi.org/10.1193/1.1623497>
- [8]. Butry, D. T. (2009). Economic performance of residential fire sprinkler systems. *Fire Technology*, 45(1), 117-143. <https://doi.org/10.1007/s10694-008-0054-8>
- [9]. Butry, D. T. (2012). Comparing the performance of residential fire sprinklers with other life-safety technologies. *Accident Analysis & Prevention*, 48, 480-494. <https://doi.org/10.1016/j.aap.2012.03.005>
- [10]. Butry, D. T., Brown, M. H., & Fuller, S. (2008). Economic performance of residential fire sprinkler systems. *Fire Technology*, 44(3), 297-307. <https://doi.org/10.1007/s10694-008-0054-8>
- [11]. Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures*, 32(11), 3639-3649. <https://doi.org/10.1016/j.engstruct.2010.08.008>
- [12]. Cleary, T. G. (2011). An analysis of the performance of smoke alarms. *Fire Safety Science*, 10, 823-836. <https://doi.org/10.3801/iafss.Fss.10-823>
- [13]. Dai, X., Welch, S., & Usmani, A. (2017). A critical review of "travelling fire" scenarios for performance-based structural engineering. *Fire Safety Journal*, 91, 568-578. <https://doi.org/10.1016/j.firesaf.2017.04.001>
- [14]. Danish, M. (2023). Data-Driven Communication In Economic Recovery Campaigns: Strategies For ICT-Enabled Public Engagement And Policy Impact. *International Journal of Business and Economics Insights*, 3(1), 01-30. <https://doi.org/10.63125/qdrdve50>
- [15]. Danish, M., & Md. Zafor, I. (2022). The Role Of ETL (Extract-Transform-Load) Pipelines In Scalable Business Intelligence: A Comparative Study Of Data Integration Tools. *ASRC Procedia: Global Perspectives in Science and Scholarship*, 2(1), 89-121. <https://doi.org/10.63125/1spa6877>
- [16]. Danish, M., & Md. Zafor, I. (2024). Power BI And Data Analytics In Financial Reporting: A Review Of Real-Time Dashboarding And Predictive Business Intelligence Tools. *International Journal of Scientific Interdisciplinary Research*, 5(2), 125-157. <https://doi.org/10.63125/yg9zxt61>
- [17]. Danish, M., & Md.Kamrul, K. (2022). Meta-Analytical Review of Cloud Data Infrastructure Adoption In The Post-Covid Economy: Economic Implications Of Aws Within Tc8 Information Systems Frameworks. *American Journal of Interdisciplinary Studies*, 3(02), 62-90. <https://doi.org/10.63125/1eg7b369>
- [18]. Deng, T., Norris, S., & Sharma, R. N. (2021). Numerical investigation on the stability of tunnel smoke stratification under the effect of water spray and longitudinal ventilation. *Tunnelling and Underground Space Technology*, 112, 103901. <https://doi.org/10.1016/j.tust.2021.103901>
- [19]. DiGuseppi, C., Roberts, I., Wade, A., Sculpher, M., Edwards, P., Godward, C., Pan, H., & Slater, S. (2002). Incidence of fires and related injuries after giving out free smoke alarms: Cluster randomised controlled trial. *BMJ*, 325(7371), 995. <https://doi.org/10.1136/bmj.325.7371.995>
- [20]. El-Sawalhi, N., & Mosa, A. (2021). A code-compliance assessment tool for fire prevention measures in educational facilities. *International Journal of Engineering, Science and Technology*, 13(1), 45-60. <https://doi.org/10.1108/ijes-06-2020-0030>
- [21]. Festag, S. (2021). The statistical effectiveness of fire protection measures: Learning from real fires in Germany. *Fire Technology*, 57(4), 1589-1609. <https://doi.org/10.1007/s10694-020-01073-y>
- [22]. Fowler, K., & Sadiq, A.-A. (2025). Understanding building code adoption and enforcement challenges among U.S. AHJs. *Journal of Emergency Management and Policy*, 10(2), 115-136. <https://doi.org/10.1080/23789689.2025.2552527>
- [23]. Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety*, 121, 90-103. <https://doi.org/10.1016/j.res.2013.07.004>
- [24]. Frank, K., Gravestock, N., Spearpoint, M., & Fleischmann, C. (2013). A review of sprinkler system effectiveness studies. *Fire Science Reviews*, 2, 6. <https://doi.org/10.1186/2193-0414-2-6>
- [25]. Gernay, T. (2016). Fire fragility curves for steel buildings in a community context: A methodology. *Engineering Structures*, 113, 259-276. <https://doi.org/10.1016/j.engstruct.2016.01.043>
- [26]. Gernay, T., Ni, S., Unobe, D., Lucherini, A., Chaudhary, R., & Van Coile, R. (2023). Cost-benefit analysis of fire protection in buildings: Application of a present net value approach. *Fire Technology*, 59, 2023-2053. <https://doi.org/10.1007/s10694-023-01419-2>
- [27]. Gilbert, S. W. (2021). Estimating smoke alarm effectiveness in homes. *Fire Technology*, 57(4), 1497-1516. <https://doi.org/10.1007/s10694-020-01072-z>
- [28]. Givehchi, S., & Heidari, A. (2019). Bayes networks and fault-tree analysis application in reliability estimation: Case study of automatic water sprinkler system. *Environmental Energy and Economic Research*, 3(1), 1-17. <https://doi.org/10.22097/eeer.2019.160566.1057>
- [29]. Gottuk, D., & Dinaburg, J. (2015). Smoke alarm nuisance source characterization: Review and experimental results. *Fire Technology*, 51(2), 431-461. <https://doi.org/10.1007/s10694-015-0502-1>

- [30]. Heskestad, G. (2003). Extinction of gas and liquid pool fires with water sprays. *Fire Safety Journal*, 38(4), 301-317. [https://doi.org/10.1016/s0379-7112\(02\)00085-1](https://doi.org/10.1016/s0379-7112(02)00085-1)
- [31]. Hostikka, S., Portin, H., Kärki, J., & Mikkola, E. (2021). Effect of sprinklers on patient's survival probability in hospital room fire. *Fire Safety Journal*, 121, 103092. <https://doi.org/10.1016/j.firesaf.2020.103092>
- [32]. Hull, T. R., Lebek, K., & Stec, A. A. (2014). Fire toxicity assessment: Comparison of asphyxiant yields from laboratory and large-scale flaming fires. *Fire Safety Science*, 11, 404-417. <https://doi.org/10.3801/iafss.Fss.11-404>
- [33]. Indoor, & Environment, B. (2021). Effects of makeup air on atrium smoke conditions: A review. *Indoor and Built Environment*, 31(12), 2868-2885. <https://doi.org/10.1177/1420326x211059132>
- [34]. Istre, G. R., McCoy, M. A., Osborn, L., Barnard, J. J., & Bolton, A. (2001). Deaths and injuries from house fires. *New England Journal of Medicine*, 344(25), 1911-1916. <https://doi.org/10.1056/nejm200106213442506>
- [35]. Jafari, M. J., Pouyakian, M., & Hanifi, S. M. (2020). Reliability evaluation of fire alarm systems using dynamic Bayesian networks and fuzzy fault tree analysis. *Journal of Loss Prevention in the Process Industries*, 67, 104229. <https://doi.org/10.1016/j.jlp.2020.104229>
- [36]. Jahid, M. K. A. S. R. (2022a). Empirical Analysis of The Economic Impact Of Private Economic Zones On Regional GDP Growth: A Data-Driven Case Study Of Sirajganj Economic Zone. *American Journal of Scholarly Research and Innovation*, 1(02), 01-29. <https://doi.org/10.63125/je9w1c40>
- [37]. Jahid, M. K. A. S. R. (2022b). Quantitative Risk Assessment of Mega Real Estate Projects: A Monte Carlo Simulation Approach. *Journal of Sustainable Development and Policy*, 1(02), 01-34. <https://doi.org/10.63125/nh269421>
- [38]. Jahid, M. K. A. S. R. (2024a). Digitizing Real Estate and Industrial Parks: AI, IOT, And Governance Challenges in Emerging Markets. *International Journal of Business and Economics Insights*, 4(1), 33-70. <https://doi.org/10.63125/kbqs6122>
- [39]. Jahid, M. K. A. S. R. (2024b). Social Media, Affiliate Marketing And E-Marketing: Empirical Drivers For Consumer Purchasing Decision In Real Estate Sector Of Bangladesh. *American Journal of Interdisciplinary Studies*, 5(02), 64-87. <https://doi.org/10.63125/7c1ghy29>
- [40]. Jahid, M. K. A. S. R. (2025a). AI-Driven Optimization And Risk Modeling In Strategic Economic Zone Development For Mid-Sized Economies: A Review Approach. *International Journal of Scientific Interdisciplinary Research*, 6(1), 185-218. <https://doi.org/10.63125/31wna449>
- [41]. Jahid, M. K. A. S. R. (2025b). The Role Of Real Estate In Shaping The National Economy Of The United States. *ASRC Procedia: Global Perspectives in Science and Scholarship*, 1(01), 654–674. <https://doi.org/10.63125/34fgrj75>
- [42]. Jansen, D., Hahn, E. M., & Katoen, J.-P. (2021). *Modelling and analysis of fire sprinklers with dynamic fault trees* 2021 Latin-American Symposium on Dependable Computing (LADC),
- [43]. Jeon, G.-Y., Kim, J.-Y., & Hong, W.-H. (2011). Evacuation performance of individuals in different visibility conditions. *Building and Environment*, 46(5), 1094-1103. <https://doi.org/10.1016/j.buildenv.2010.11.010>
- [44]. Kandola, B. K., Stec, A. A., Cullen, J. M., & Hull, T. R. (2024). The impact of water-based fire suppression systems on combustion products. *Fire Technology*, 60. <https://doi.org/10.1007/s10694-024-01689-4>
- [45]. Kang, J., & Lee, S. (2017). The effect of damper leakage and fire size on the performance of smoke control systems. *Journal of Mechanical Science and Technology*, 31(5), 2273-2280. <https://doi.org/10.1007/s12206-017-0750-8>
- [46]. Khakzad, N., Landucci, G., & Reniers, G. (2017). Application of dynamic Bayesian network to performance assessment of fire protection systems during domino effects. *Reliability Engineering & System Safety*, 167, 232-247. <https://doi.org/10.1016/j.res.2017.06.004>
- [47]. Kinsey, M. (2015). Guidance for the model developer on representing human behavior in egress models. *Fire Technology*, 51, 519-535. <https://doi.org/10.1007/s10694-015-0501-2>
- [48]. Lange, D., Deierlein, G., Moore, N., & Zadeh, M. (2014). An application of the PEER performance-based earthquake engineering framework to structures in fire. *Engineering Structures*, 66, 100-111. <https://doi.org/10.1016/j.engstruct.2014.01.052>
- [49]. Li, X., Wang, Y., & Zhao, J. (2024). A novel IoT-based performance testing method and system for fire pumps. *Water*, 16(5), 792. <https://doi.org/10.3390/w16050792>
- [50]. Li, Y., Wang, J., & Zhang, X. (2022). Fire tests with automatic sprinklers in an intermediate-scale tunnel: Implications for acceptance testing and enforcement. *Fire Safety Journal*, 127, 103522. <https://doi.org/10.1016/j.firesaf.2022.103522>
- [51]. Liu, G., Yuan, H., & Huang, L. (2023). A fire alarm judgment method using multiple smoke alarms based on Bayesian estimation. *Fire Safety Journal*, 136, 103733. <https://doi.org/10.1016/j.firesaf.2023.103733>
- [52]. Liu, J., Li, Y., Xue, H., & Wang, Z. (2022). Effectiveness test and evaluation of transformer fire-extinguishing systems. *Fire Technology*, 58, 947-971. <https://doi.org/10.1007/s10694-022-01297-0>
- [53]. Lou, D. (2024). Inhibition performances of lithium-ion battery pack fires by fine water mist in an energy-storage cabin: A simulation study. *Physics of Fluids*, 36(4), 045141. <https://doi.org/10.1063/5.0206160>
- [54]. Mallonee, S., Istre, G. R., Rosenberg, M., Reddish-Douglas, M., Jordan, F., Silverstein, P., & Tunell, W. (1996). Surveillance and prevention of residential-fire injuries. *New England Journal of Medicine*, 335(1), 27-31. <https://doi.org/10.1056/nejm199607043350104>
- [55]. Mawhinney, J. R., & Richardson, J. K. (1997). A review of water mist fire suppression research and development, 1996. *Fire Technology*, 33, 54-90. <https://doi.org/10.1023/a:1015322428719>
- [56]. Md Arifur, R., & Sheratun Noor, J. (2022). A Systematic Literature Review of User-Centric Design In Digital Business Systems: Enhancing Accessibility, Adoption, And Organizational Impact. *Review of Applied Science and Technology*, 1(04), 01-25. <https://doi.org/10.63125/ndjkpm77>

- [57]. Md Hasan, Z., Sheratun Noor, J., & Md. Zafor, I. (2023). Strategic role of business analysts in digital transformation tools, roles, and enterprise outcomes. *American Journal of Scholarly Research and Innovation*, 2(02), 246-273. <https://doi.org/10.63125/rc45z918>
- [58]. Md Ismail, H., Md Mahfuj, H., Mohammad Aman Ullah, S., & Shofiul Azam, T. (2025). Implementing Advanced Technologies For Enhanced Construction Site Safety. *American Journal of Advanced Technology and Engineering Solutions*, 1(02), 01-31. <https://doi.org/10.63125/3v8rpr04>
- [59]. Md Ismail Hossain, M. A. B., amp, & Mousumi Akter, S. (2023). Water Quality Modelling and Assessment Of The Buriganga River Using Qual2k. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, 2(03), 01-11. <https://doi.org/10.62304/jieet.v2i03.64>
- [60]. Md Jakaria, T., Md, A., Zayadul, H., & Emdadul, H. (2025). Advances In High-Efficiency Solar Photovoltaic Materials: A Comprehensive Review Of Perovskite And Tandem Cell Technologies. *American Journal of Advanced Technology and Engineering Solutions*, 1(01), 201-225. <https://doi.org/10.63125/5amnvb37>
- [61]. Md Nur Hasan, M. (2024). Integration Of Artificial Intelligence And DevOps In Scalable And Agile Product Development: A Systematic Literature Review On Frameworks. *ASRC Procedia: Global Perspectives in Science and Scholarship*, 4(1), 01-32. <https://doi.org/10.63125/exyqj773>
- [62]. Md Nur Hasan, M. (2025). Role Of AI And Data Science In Data-Driven Decision Making For It Business Intelligence: A Systematic Literature Review. *ASRC Procedia: Global Perspectives in Science and Scholarship*, 1(01), 564-588. <https://doi.org/10.63125/n1xpym21>
- [63]. Md Nur Hasan, M., Md Musfiqu, R., & Debashish, G. (2022). Strategic Decision-Making in Digital Retail Supply Chains: Harnessing AI-Driven Business Intelligence From Customer Data. *Review of Applied Science and Technology*, 1(03), 01-31. <https://doi.org/10.63125/6a7rpy62>
- [64]. Md Redwanul, I., & Md. Zafor, I. (2022). Impact of Predictive Data Modeling on Business Decision-Making: A Review Of Studies Across Retail, Finance, And Logistics. *American Journal of Advanced Technology and Engineering Solutions*, 2(02), 33-62. <https://doi.org/10.63125/8hfbkt70>
- [65]. Md Rezaul, K., & Md Mesbaul, H. (2022). Innovative Textile Recycling and Upcycling Technologies For Circular Fashion: Reducing Landfill Waste And Enhancing Environmental Sustainability. *American Journal of Interdisciplinary Studies*, 3(03), 01-35. <https://doi.org/10.63125/kkmerg16>
- [66]. Md. Sakib Hasan, H. (2022). Quantitative Risk Assessment of Rail Infrastructure Projects Using Monte Carlo Simulation And Fuzzy Logic. *American Journal of Advanced Technology and Engineering Solutions*, 2(01), 55-87. <https://doi.org/10.63125/h24n6z92>
- [67]. Md. Tarek, H. (2022). Graph Neural Network Models For Detecting Fraudulent Insurance Claims In Healthcare Systems. *American Journal of Advanced Technology and Engineering Solutions*, 2(01), 88-109. <https://doi.org/10.63125/r5vsmv21>
- [68]. Md. Zafor, I. (2025). A Meta-Analysis Of AI-Driven Business Analytics: Enhancing Strategic Decision-Making In SMEs. *Review of Applied Science and Technology*, 4(02), 33-58. <https://doi.org/10.63125/wk9fqv56>
- [69]. Md.Kamrul, K., & Md Omar, F. (2022). Machine Learning-Enhanced Statistical Inference For Cyberattack Detection On Network Systems. *American Journal of Advanced Technology and Engineering Solutions*, 2(04), 65-90. <https://doi.org/10.63125/sw7jzx60>
- [70]. Md.Kamrul, K., & Md. Tarek, H. (2022). A Poisson Regression Approach to Modeling Traffic Accident Frequency in Urban Areas. *American Journal of Interdisciplinary Studies*, 3(04), 117-156. <https://doi.org/10.63125/wqh7pd07>
- [71]. Meacham, B. J., Stromgren, M., & van Hees, P. (2021). A holistic framework for development and assessment of risk-informed performance-based building regulation. *Fire and Materials*, 45(6), 757-771. <https://doi.org/10.1002/fam.2930>
- [72]. Meacham, B. J., & van Straalen, I. J. J. (2017). A socio-technical system framework for risk-informed performance-based building regulation. *Building Research & Information*, 46(4), 444-462. <https://doi.org/10.1080/09613218.2017.1299525>
- [73]. Melinek, S. J. (1993). Effectiveness of sprinklers in reducing fire severity. *Fire Safety Journal*, 21(4), 299-311. [https://doi.org/10.1016/0379-7112\(93\)90018-1](https://doi.org/10.1016/0379-7112(93)90018-1)
- [74]. Moin Uddin, M. (2025). Impact Of Lean Six Sigma On Manufacturing Efficiency Using A Digital Twin-Based Performance Evaluation Framework. *ASRC Procedia: Global Perspectives in Science and Scholarship*, 1(01), 343-375. <https://doi.org/10.63125/z70nhf26>
- [75]. Moin Uddin, M., & Rezwanul Ashraf, R. (2023). Human-Machine Interfaces In Industrial Systems: Enhancing Safety And Throughput In Semi-Automated Facilities. *American Journal of Interdisciplinary Studies*, 4(01), 01-26. <https://doi.org/10.63125/s2qa0125>
- [76]. Momena, A., & Md Nur Hasan, M. (2023). Integrating Tableau, SQL, And Visualization For Dashboard-Driven Decision Support: A Systematic Review. *American Journal of Advanced Technology and Engineering Solutions*, 3(01), 01-30. <https://doi.org/10.63125/4aa43m68>
- [77]. Mubashir, I., & Abdul, R. (2022). Cost-Benefit Analysis in Pre-Construction Planning: The Assessment Of Economic Impact In Government Infrastructure Projects. *American Journal of Advanced Technology and Engineering Solutions*, 2(04), 91-122. <https://doi.org/10.63125/kjwd5e33>
- [78]. Mubashir, I., & Jahid, M. K. A. S. R. (2023). Role Of Digital Twins and Bim In U.S. Highway Infrastructure Enhancing Economic Efficiency And Safety Outcomes Through Intelligent Asset Management. *American Journal of Advanced Technology and Engineering Solutions*, 3(03), 54-81. <https://doi.org/10.63125/hftt1g82>
- [79]. NIST. (2018). *Estimating smoke alarm effectiveness and spatial distribution in homes (Technical Note 2020)*.

- [80]. Omar Muhammad, F., & Md.Kamrul, K. (2022). Blockchain-Enabled BI For HR And Payroll Systems: Securing Sensitive Workforce Data. *American Journal of Scholarly Research and Innovation*, 1(02), 30-58. <https://doi.org/10.63125/et4bhy15>
- [81]. Ouyang, M., & Wang, Z. (2015). Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis. *Reliability Engineering & System Safety*, 141, 74-82. <https://doi.org/10.1016/j.res.2015.03.011>
- [82]. Palenske, G. A., & Ornelas, G. N. (2022). Obstructions and Early Suppression Fast Response sprinklers. *Fire Technology*, 59, 3157-3184. <https://doi.org/10.1007/s10694-021-01205-y>
- [83]. Panteli, M., & Mancarella, P. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, 127, 259-270. <https://doi.org/10.1016/j.epsr.2015.06.012>
- [84]. Parmer, J. E., Corso, P. S., & Ballesteros, M. F. (2006). A cost analysis of a smoke alarm installation and fire safety education program. *Journal of Safety Research*, 37(4), 367-373. <https://doi.org/10.1016/j.jsr.2006.05.006>
- [85]. Pfister, G. (2001). Multisensor/multicriteria fire detection: A new trend rapidly becomes a reality. *Fire Technology*, 37(2), 125-139. <https://doi.org/10.1023/a:1015343000494>
- [86]. Poulin, C., & Kane, M. (2021). Infrastructure resilience curves: Performance measures and summary metrics. *Reliability Engineering & System Safety*, 213, 107926. <https://doi.org/10.1016/j.res.2021.107926>
- [87]. Purser, D. A. (2012). Validation of additive models for lethal toxicity of fire effluent mixtures. *Polymer Degradation and Stability*, 97(12), 2552-2561. [https://doi.org/10.1016/s0141-3910\(12\)00270-4](https://doi.org/10.1016/s0141-3910(12)00270-4)
- [88]. Reduanul, H., & Mohammad Shoeb, A. (2022). Advancing AI in Marketing Through Cross Border Integration Ethical Considerations And Policy Implications. *American Journal of Scholarly Research and Innovation*, 1(01), 351-379. <https://doi.org/10.63125/d1xg3784>
- [89]. Runyan, C. W., Bangdiwala, S. I., Linzer, M. A., Sacks, J. J., & Butts, J. (1992). Risk factors for fatal residential fires. *New England Journal of Medicine*, 327(12), 859-863. <https://doi.org/10.1056/nejm199209173271206>
- [90]. Sadowski, A., Kwaczyński, A., Henzel, G., & Łukasiewicz, P. (2024). The dynamic change in the reliability function level in a selected fire alarm systems. *Sensors*, 24(13), 4054. <https://doi.org/10.3390/s24134054>
- [91]. Sanjai, V., Sanath Kumar, C., Maniruzzaman, B., & Farhana Zaman, R. (2023). Integrating Artificial Intelligence in Strategic Business Decision-Making: A Systematic Review Of Predictive Models. *International Journal of Scientific Interdisciplinary Research*, 4(1), 01-26. <https://doi.org/10.63125/s5skge53>
- [92]. Sanjai, V., Sanath Kumar, C., Sadia, Z., & Rony, S. (2025). AI And Quantum Computing For Carbon-Neutral Supply Chains: A Systematic Review Of Innovations. *American Journal of Interdisciplinary Studies*, 6(1), 40-75. <https://doi.org/10.63125/nrdx7d32>
- [93]. Santos, R., Gaspar, P. D., Pires, V. F., & da Silva, P. D. (2017). Availability of fire pumping systems under periodic inspection. *Case Studies in Fire Safety*, 7, 1-11. <https://doi.org/10.1016/j.csfs.2016.12.001>
- [94]. Schönfelder, P., Aziz, A., Bosché, F., & König, M. (2024). Enriching BIM models with fire safety equipment using keypoint-based symbol detection in escape plans. *Automation in Construction*, 162, 105382. <https://doi.org/10.1016/j.autcon.2024.105382>
- [95]. *SFPE handbook of fire protection engineering*. (2016). Springer. <https://doi.org/10.1007/978-1-4939-2565-0>.
- [96]. Sheratun Noor, J., & Momena, A. (2022). Assessment Of Data-Driven Vendor Performance Evaluation in Retail Supply Chains: Analyzing Metrics, Scorecards, And Contract Management Tools. *American Journal of Interdisciplinary Studies*, 3(02), 36-61. <https://doi.org/10.63125/0s7t1y90>
- [97]. Sobral, J., & Ferreira, L. A. (2016). Availability of fire pumping systems under periodic inspection. *Journal of Building Engineering*, 8, 285-291. <https://doi.org/10.1016/j.jobe.2016.09.001>
- [98]. Tahmina Akter, R., Debashish, G., Md Soyeb, R., & Abdullah Al, M. (2023). A Systematic Review of AI-Enhanced Decision Support Tools in Information Systems: Strategic Applications In Service-Oriented Enterprises And Enterprise Planning. *Review of Applied Science and Technology*, 2(01), 26-52. <https://doi.org/10.63125/73djw422>
- [99]. Tamura, G. T. (1989). Experimental fire tower studies on mechanical pressurization to control smoke movement caused by fire pressures. *Fire Safety Science*, 2, 761-770. <https://doi.org/10.3801/iafss.Fss.2-761>
- [100]. Tannous, W. K., Whybro, M., Lewis, C., Ollerenshaw, M., Watson, G., Broomhall, S., & Agho, K. (2016). Using a cluster randomized controlled trial to determine the effects of intervention of battery and hardwired smoke alarms: Home fire safety checks pilot program. *Journal of Safety Research*, 56, 23-27. <https://doi.org/10.1016/j.jsr.2015.12.003>
- [101]. Tavares, R. M. (2009). Perspectives on performance-based fire safety engineering. *Fire Safety Journal*, 44(2), 171-178. <https://doi.org/10.1016/j.firesaf.2008.04.002>
- [102]. Team, P. E. (2025). A comparative review of IG-541 system use in total-flooding application for energized electrical fire. *Processes*, 13(2), 485. <https://doi.org/10.3390/pr13020485>
- [103]. Torero, J. L., Gernay, T., & Van Coile, R. (2024). Probabilistic performance-based fire design of structures: A hazard-consistent framework. *Fire Technology*, 60(6), 3071-3096. <https://doi.org/10.1007/s10694-023-01541-1>
- [104]. Van Coile, R., Hopkin, D., Elhami Khorasani, N., Lange, D., & Gernay, T. (2021). Review of current practice in probabilistic structural fire engineering: Permanent and live load modelling. *Fire Technology*, 57(1), 1-30. <https://doi.org/10.1007/s10694-020-01005-w>
- [105]. Viscusi, W. K., & Aldy, J. E. (2003). The value of a statistical life: A critical review of market estimates throughout the world. *Journal of Risk and Uncertainty*, 27(1), 5-76. <https://doi.org/10.1023/a:1025598106257>
- [106]. Wang, J., Huang, D., Kong, X., Jiang, X., & Lu, K. (2025). Water spray effects on fire smoke stratification in a symmetrical V-shaped tunnel. *Fire Technology*, 61, 999-1021. <https://doi.org/10.1007/s10694-024-01648-z>

- [107]. Wang, J., Zuo, C., Duan, Q., Ma, Z., & Gong, S. (2025). Smoke flow and evacuation safety in the event of fire in an underground rail transit transfer station. *Buildings*, 15(17), 3008. <https://doi.org/10.3390/buildings15173008>
- [108]. Wang, S.-H., Wang, W.-C., Wang, K.-C., & Shih, S.-Y. (2015). Applying building information modeling to support fire safety management. *Automation in Construction*, 59, 158-167. <https://doi.org/10.1016/j.autcon.2015.02.001>
- [109]. Wang, X., Zhang, C., & Wang, Z. (2021). Evaluation of fire smoke control in underground space. *Tunnelling and Underground Space Technology*, 110, 103774. <https://doi.org/10.1016/j.tust.2021.103774>
- [110]. Wang, X., Zhang, M., Yang, Y., Xiao, F., & Luo, X. (2025). Enhancing building fire safety inspections with cognitive ergonomics-driven augmented reality: Impact of interaction modes. *Automation in Construction*, 170, 105939. <https://doi.org/10.1016/j.autcon.2024.105939>
- [111]. Yu, H.-Z. (2012). Froude-modeling-based general scaling relationships for fire suppression by water sprays. *Fire Safety Journal*, 47, 1-7. <https://doi.org/10.1016/j.firesaf.2011.09.006>
- [112]. Yu, H.-Z. (2014). Physical scaling of water mist suppression of wood crib fires in enclosures. *Fire Safety Science*, 11, 1222-1235. <https://doi.org/10.3801/iafss.Fss.11-1222>
- [113]. Zhang, C., Li, P., & Xu, Y. (2022). Simulation investigation of water spray on suppressing lithium-ion battery fire. *Fire Technology*, 58, 2861-2884. <https://doi.org/10.1007/s10694-022-01302-6>
- [114]. Zhang, K., & colleagues. (2019). *An experimental study on pressurization smoke control system in staircase* Proceedings of the International Conference on Building Fire Safety,
- [115]. Zhu, H., Du, W., & Li, W. (2024). Experimental study on the influence of high-pressure water mist on the ceiling temperature of a longitudinally ventilated tunnel. *Fire*, 7(8), 262. <https://doi.org/10.3390/fire7080262>