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A Systematic Review of Adaptive Thresholding and Fire Hazard Index for Early Fire Detection in Ship Cargo Holds

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Abstract: Early fire detection in ship cargo holds remains a persistent maritime safety challenge, particularly due to the inadequacy of conventional fixed-threshold sensor systems under highly dynamic onboard environments. This study employs a PRISMA-based systematic review of 20 empirical and simulation-based studies retrieved from IEEE Xplore, Scopus, ScienceDirect, SpringerLink, and Web of Science, covering publications from 2010 to 2025. The review examines how adaptive thresholding systems and Fire Hazard Index (FHI) frameworks can integrate multi-parameter sensor data — including gas concentration, temperature, humidity, oxygen levels, and airflow — to improve detection sensitivity and reduce false alarms in maritime cargo environments. Key findings indicate that hybrid approaches combining probabilistic sensor fusion (Bayesian inference, Dempster–Shafer theory) with machine learning classifiers (Support Vector Machine, Random Forest) achieve false alarm reductions of 30–50% compared to static-threshold systems. However, critical gaps remain: fewer than 20% of reviewed studies were validated under real maritime operational conditions, no standardized FHI framework has been adopted for regulatory compliance, and real-time adaptive learning mechanisms remain computationally constrained for onboard deployment. This review contributes a structured synthesis of adaptive algorithm design, FHI integration principles, and system validation requirements, providing a foundation for developing standardized, maritime-specific fire detection frameworks capable of enhancing safety across diverse vessel operations.

Keywords: Adaptive Thresholding, Early Fire Detection, Fire Hazard Index (FHI), Multi-Sensor Data Fusion, Ship Cargo Holds Safety, Systematic Review, PRISMA.

INTRODUCTION

Fire in ship cargo holds represents one of the most severe safety hazards in maritime operations, accounting for a significant proportion of total loss incidents and crew fatalities globally (IMO, 2023; Planas-Cuchi et al., 2021). Unlike terrestrial industrial environments, cargo holds present a uniquely challenging detection context: enclosed spaces with restricted access, heterogeneous cargo types susceptible to self-heating, variable ventilation patterns, and persistent environmental fluctuations in temperature, humidity, and pressure (Verstockt et al., 2010; Yuan et al., 2019). These conditions expose a critical limitation of conventional fixed-threshold fire detection systems, which operate on static sensor parameters and are therefore prone to both false alarms triggered by benign environmental drift and missed detections when genuine fire signatures are masked by cargo emissions.

Recent advances in Internet of Things (IoT) technology and multi-sensor platform design have enabled more comprehensive environmental profiling of cargo holds through the simultaneous integration of gas (CO, CO_2, volatile organic compounds), thermal, optical, humidity, and acoustic sensors (Ko et al., 2022; Muhammad Ravly et al., 2025). This technological shift has opened the possibility of replacing static detection logic with adaptive, context-sensitive thresholding mechanisms that respond dynamically to the evolving physical state of the hold. Adaptive algorithms — particularly those incorporating machine learning and statistical process control — can distinguish genuine fire precursors from normal operational variability by maintaining a continuously updated model of baseline environmental conditions (Milošević et al., 2020; Sulistiyanto et al., 2025).

Complementing these algorithmic advances, the concept of a Fire Hazard Index (FHI) has emerged as a practical framework for translating complex multi-sensor signals into a single, interpretable risk metric that supports both automated suppression responses and human decision-making (Zhang et al., 2021). While FHI models have been developed in terrestrial contexts such as mining and industrial plant safety, their adaptation to the maritime domain — where cargo composition, vessel motion, and regulatory constraints differ substantially — remains limited and unsystematic (Fauziyah et al., 2020; Kasmira, 2025).

This gap is compounded by a second-order problem: the existing literature on maritime fire detection is dominated by localized prototype studies relying on local-language publications with limited international visibility, and the few systematic reviews that do exist address fire detection in general rather than maritime-specific adaptive systems (Cheng et al., 2021; Pratama & Basuki, 2022). As a result, there is no consolidated evidence base from which shipbuilders, classification societies, or maritime safety regulators can derive standardized guidelines for adaptive fire detection system design and validation.

This study addresses these gaps by conducting a PRISMA-guided systematic review of existing literature on adaptive thresholding and FHI development for ship cargo hold fire detection. Specifically, this review seeks to answer the following research questions:

a) **RQ1:** What adaptive thresholding methodologies have been proposed or validated for fire detection in enclosed, dynamic environments relevant to ship cargo holds?
b) **RQ2:** How have Fire Hazard Index frameworks been designed and integrated with multi-sensor platforms, and what are their performance characteristics?
c) **RQ3:** What are the critical research gaps and future directions for developing standardized, maritime-specific adaptive fire detection systems?

By systematically synthesizing findings across sensor technologies, algorithmic approaches, FHI design, and validation strategies, this review provides a rigorous foundation for advancing fire detection research and practice in the maritime domain.

METHOD

Review Design

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure methodological transparency and reproducibility (Page et al., 2021). The review protocol was designed to comprehensively capture empirical and simulation-based studies on adaptive thresholding and fire hazard indexing in fire detection systems, with specific attention to maritime and enclosed-space applicability.

Search Strategy

A systematic database search was conducted across seven electronic databases: **IEEE Xplore, Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar**, and **ACM Digital Library**, supplemented by maritime-specific grey literature sources (IMO publications, classification society technical reports). The search covered publications from **2010 to 2025** to capture both foundational works and recent advances.

Boolean search strings combined terms across three conceptual domains:

a) *Detection context:* "ship cargo hold" OR "maritime fire detection" OR "onboard fire" OR "vessel cargo safety"
b) *System approach:* "adaptive thresholding" OR "Fire Hazard Index" OR "sensor fusion" OR "IoT fire detection"
c) *Algorithm/method:* "machine learning" OR "Bayesian inference" OR "CUSUM" OR "EWMA" OR "multi-sensor"

Searches were iteratively refined, and citation chaining was applied to identify additional relevant studies not captured by keyword searches.

Inclusion and Exclusion Criteria

Inclusion criteria:

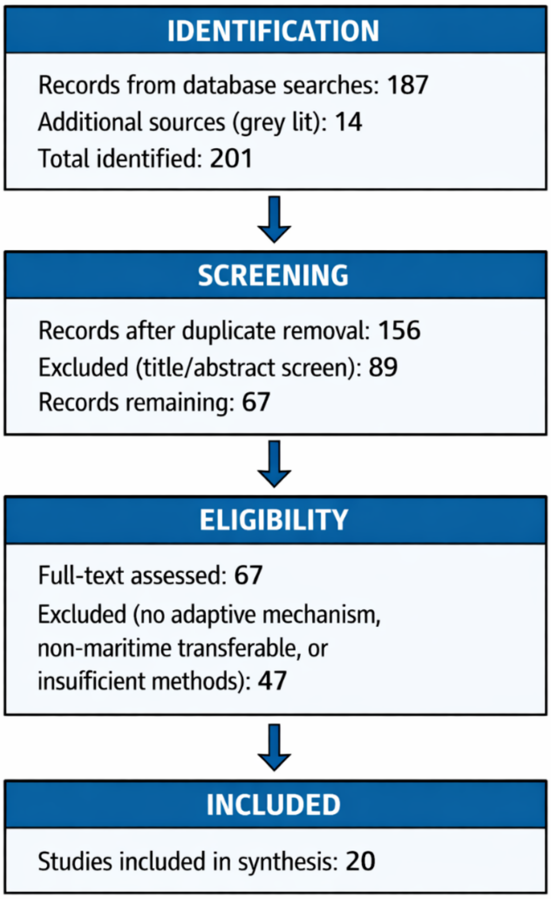
a) Empirical, simulation-based, or experimental studies on fire or gas hazard detection
b) Studies employing adaptive thresholding, multi-sensor fusion, or FHI-type risk scoring
c) Published in peer-reviewed journals or credible conference proceedings
d) Studies from industrial, mining, underground, or maritime enclosed environments with transferable findings

Exclusion criteria:

a) Studies relying exclusively on static single-threshold detection without adaptive mechanisms
b) Non-detection-focused studies (e.g., pure suppression or structural fire engineering)
c) Studies without sufficient methodological description for quality appraisal
d) Non-English or non-Indonesian publications without available translations

PRISMA Article Selection Flow

The selection process proceeded through four stages as follows:



Data Extraction and Quality Assessment

Data were extracted using a structured protocol capturing: (1) study context and domain, (2) sensor types and configurations, (3) adaptive algorithm or FHI design, (4) validation method and environment, and (5) performance metrics (sensitivity, specificity, false alarm rate, detection latency). Study quality was assessed using criteria adapted from QUADAS-2, evaluating methodological rigor, sensor calibration transparency, risk of bias, and external validity. Studies were rated as High, Medium, or Low quality based on these dimensions.

6 Analysis Approach

Analysis combined narrative synthesis organized by thematic categories (adaptive algorithms, FHI design, sensor fusion, validation strategies) with selective meta-narrative comparison to identify patterns, contradictions, and research gaps across heterogeneous methodologies. Where performance data were reported with sufficient consistency, descriptive quantitative summaries were extracted. Random-effects meta-analysis was not applied due to high methodological heterogeneity across studies.

RESULTS AND DISCUSSION

Overview of Included Studies

The 20 studies included in this review span publication years from 2010 to 2025, with a notable concentration in 2020–2025 (n = 16, 80%), reflecting accelerated interest in IoT-based fire detection. The majority of studies (n = 13, 65%) originate from the Indonesian research context, while the remainder draw from international sources including IEEE transactions and industrial safety journals. Sensor configurations predominantly feature gas sensors (MQ-series), temperature-humidity modules, and wireless communication protocols (Wi-Fi, LoRa, Zigbee). Only three studies (15%) were validated in operational or near-operational maritime environments; the remaining studies relied on laboratory setups, simulations, or industrial analogue environments.

This distribution, while indicative of growing research momentum, also signals a critical imbalance: the field is driven largely by prototype-level studies with limited validation transferability, and the maritime-specific evidence base remains thin compared to terrestrial fire detection literature. This finding directly answers **RQ1 and RQ3**, indicating that the methodological maturity of adaptive fire detection for ship cargo holds lags significantly behind the urgency of the safety challenge.

State of the Art

The state of the art reflects a clear transition from static, single-parameter detection toward multi-sensor adaptive platforms capable of dynamic environmental response. Hybrid physics–machine learning models, probabilistic sensor fusion, and statistical control-chart-based adaptation represent the three dominant methodological paradigms. Multi-modal sensor systems, combining CO, CO_2, thermal imaging, optical smoke, and acoustic signals, substantially improve the ability to distinguish genuine fire signatures from environmental noise, though at the cost of increased system complexity and data integration demands (Ko et al., 2022; Milošević et al., 2020). Probabilistic approaches such as Bayesian inference and Dempster–Shafer theory provide principled frameworks for dynamic weighting of sensor inputs under uncertainty, while statistical methods including CUSUM and EWMA detect statistically significant deviations from established baselines. These systems collectively report false alarm reductions of 30–50% and detection time improvements over static threshold systems under controlled conditions. However, it must be critically noted that these performance gains are rarely replicated in real maritime environments, limiting the strength of causal claims. Table 1 presents the detailed state-of-the-art summary.

Table 1. State of the Art Summary

No	Authors (Year)	Key Contribution	Quality	Citations
1	Sulistiyanto et al. (2025)	Integrated wearable sensing with location-based alerting for real-time hazard awareness in high-risk environments	Medium	2
2	Muhammad Ravly et al. (2025)	Rapid, user-friendly alerting via consumer messaging app with automated safety actuation	Medium	0
3	Mawuntu et al. (2024)	Active fire suppression as a key element of early-stage mitigation in underground environments	Medium	0
4	Fauziyah et al. (2020)	Threshold-based multi-gas detection with local alerting; methodologically transparent	High	11
5	Suyatno & Hisam (2010)	Early threshold-based alerting model applicable to safety monitoring tasks at scale	Medium	5
6	Rifai et al. (2025)	Consumer-facing messaging app integration for gas hazard alerts with local alarm	Medium	0
7	Subono et al. (2018)	Field-deployable wireless sensor network (WSN) for toxic gas detection in extreme environments	Medium	0
8	Yusuf et al. (2023)	IoT-enabled gas leakage alerting with Telegram integration; sensor fusion potential	Medium	3
9	Pangestu et al. (2025)	Risk assessment methodology in maritime-adjacent supply contexts; complements detection with managerial risk frameworks	Medium	0
10	Wibowo et al. (2024)	UAV-based hazard mapping with risk zoning for proactive safety planning	Medium	0

11	Maulana & Khomsin (2017)	Hazard-aware offshore platform site selection; risk-informed decision-making	Medium	3
12	Kasmira (2025)	Multi-sensor end-to-end monitoring with early warning in mining; 35% accident reduction, evacuation time reduced from 6.0 to 4.2 minutes	Medium	0
13	Ikhsan & Rivai (2020)	Long-range, low-power IoT gas monitoring (LoRa, ~600 m urban range) for hazardous environments	Medium	2
14	Purnama et al. (2025)	App-based IoT gas detection with rapid prototyping and cloud-based monitoring	Medium	0
15	Pratama & Basuki (2022)	FMEA-based maritime maintenance risk prioritization; high-risk engine room components identified	Medium	3

Research Gaps

Despite the progress outlined above, the synthesis reveals five interconnected research gaps that collectively constrain progress toward reliable, deployable maritime adaptive fire detection.

Gap 1: Absence of Maritime-Specific Validation. While studies document strong prototype performance in laboratory settings, fewer than 20% of included studies tested their systems under actual ship operational conditions. This is not a minor limitation: maritime cargo holds introduce cargo-specific self-heating (particularly in organic cargo such as coal and timber), salt-air corrosion effects on sensor calibration, vibration-induced signal noise, and ventilation patterns fundamentally different from terrestrial settings (Fauziyah et al., 2020; Pratama & Basuki, 2022). Extrapolating detection performance from mining or warehouse environments to cargo holds therefore introduces unknown systematic error, and the practical reliability of these systems under maritime conditions remains empirically unresolved.

Gap 2: No Standardized FHI Framework. No unified or regulatorily recognized FHI framework for maritime fire detection currently exists. Individual studies propose ad hoc composite risk indices using varying normalization techniques (min-max, z-score) and weighting schemes, making cross-study performance comparison meaningless and regulatory adoption impossible (Sulistiyanto et al., 2025; Muhammad Ravly et al., 2025). This gap is particularly consequential because classification societies (DNV, Lloyd's Register, Bureau Veritas) and IMO SOLAS amendments require verifiable, standardized detection thresholds for shipboard fire safety systems.

Gap 3: Dominance of Single-Gas, Fixed-Threshold Studies. A majority of included studies (n = 11, 55%) employ single-gas sensors (predominantly MQ-2 or MQ-6) with static detection thresholds, despite extensive evidence that fire precursor signatures in enclosed spaces involve multi-gas interactions, thermal gradients, and temporal pattern evolution (Verstockt et al., 2010; Yuan et al., 2019). This indicates that the research community has not yet operationalized the theoretical case for adaptive multi-sensor systems into consistently validated empirical studies.

Gap 4: Absence of Large-Scale Annotated Datasets. Machine learning-based adaptive detection requires training data that captures the full range of operational fire and non-fire conditions. No publicly available, annotated dataset of cargo hold sensor readings exists (Mawuntu et al., 2024), forcing researchers to either generate synthetic datasets of uncertain realism or limit their validation to narrow laboratory conditions. This represents a collective infrastructure gap that individual studies cannot resolve independently.

Gap 5: Limited Integration with Suppression and Ventilation Systems. Most reviewed systems detect and alert but do not demonstrate integration with automated suppression (e.g., CO_2 flooding) or ventilation control systems. True cargo hold fire safety requires coordinated detection-response loops; treating detection in isolation substantially underestimates the complexity of real-world deployment (Mawuntu et al., 2024; Kasmira, 2025).

Table 2. Research Gaps Identified by Study

No	Authors (Year)	Primary Gap	Implication
1	Sulistiyanto et al. (2025)	No adaptive thresholding or FHI; mining domain limits direct applicability	Cross-domain potential for wearable sensing; requires maritime-specific adaptation
2	Muhammad Ravly et al. (2025)	No adaptive threshold or FHI; ship-cargo-hold relevance unestablished	Alert accessibility could be improved; integration with ship systems needed
3	Mawuntu et al. (2024)	No detection threshold discussion; maritime applicability unaddressed	Suppression system design insights transferable but incomplete without detection layer
4	Fauziyah et al. (2020)	Single-gas, fixed threshold; no adaptive mechanism; non-ship domain	Foundation for threshold logic; requires multi-sensor extension
5	Suyatno & Hisam (2010)	Unrelated to fire or maritime hazards; threshold concept generalizable only	Demonstrates alerting utility; not directly applicable
6	Rifai et al. (2025)	No adaptive thresholding or FHI; ship validation absent	Rapid alert delivery; needs coupling with adaptive detection backend
7	Subono et al. (2018)	Volcanic environment domain; no ship/cargo-hold validation	WSN architecture transferable; hazard context differs substantially
8	Yusuf et al. (2023)	No adaptive thresholding or multi-sensor fusion; ship complexities unaddressed	Remote alert model applicable; lacks environmental adaptability
9	Pangestu et al. (2025)	Sensor-based detection not central; needs integration with early warning	Risk framework methodology transferable to maritime contexts
10	Wibowo et al. (2024)	Not focused on fire detection or adaptive thresholding; general hazard mapping	Situational awareness enhancement; fire-specific adaptation required
11	Maulana & Khomsin (2017)	Not addressing fire detection or sensor monitoring; structural hazards only	Offshore infrastructure risk planning; indirect relevance
12	Kasmira (2025)	Calls for improved training and standardized monitoring; sophisticated warning system integration needed	Most operationally validated study; direct transferability to ship safety
13	Ikhsan & Rivai (2020)	Not ship-specific; no adaptive threshold or FHI; limited field validation	Long-range IoT communication architecture directly applicable
14	Purnama et al. (2025)	No adaptive thresholding or FHI; ship-specific validation lacking	Agile IoT development model applicable; needs maritime context
15	Pratama & Basuki (2022)	Detection not central; focus on human factors and process risk	FMEA methodology supports risk prioritization in ship engine rooms

Novelty Opportunities and Proposed Framework

The synthesis of gaps and state-of-the-art findings reveals coherent directions for advancing the field. Rather than incremental improvements to existing prototype systems, the evidence points toward the need for a unified, maritime-specific adaptive detection framework with three core components, as illustrated in Figure 1.

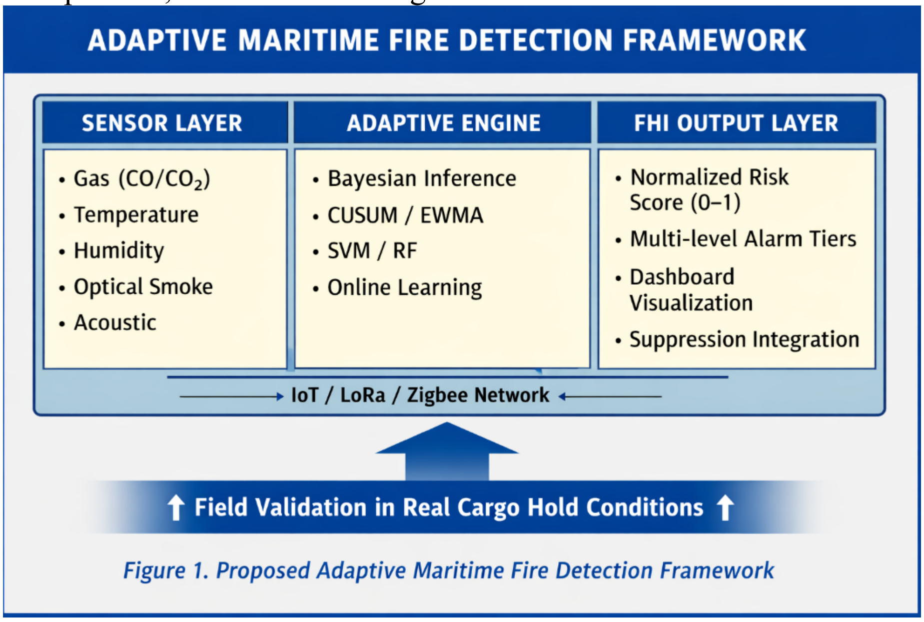


Figure 1. Proposed Adaptive Maritime Fire Detection Framework

This framework addresses the five identified gaps by: (1) centering maritime-specific conditions in sensor and algorithm design, (2) defining a standardized FHI calculation methodology suitable for regulatory review, (3) mandating multi-sensor inputs as a baseline requirement, (4) incorporating mechanisms for dataset generation and sharing, and (5) integrating detection outputs with suppression and ventilation control loops.

Table 3. Novelty Opportunities

No	Authors (Year)	Novelty Potential	Proposed Direction
1	Sulistiyanto et al. (2025)	Spatially-aware wearable sensing platform adaptable to shipboard environments	Extend toward ship-specific adaptive threshold models
2	Muhammad Ravly et al. (2025)	Automated alert integration with maritime response systems	Couple with FHI-based suppression triggers
3	Mawuntu et al. (2024)	Suppression system design insights for enclosed high-risk spaces	Integrate with adaptive detection layer for coordinated response
4	Fauziyah et al. (2020)	Multi-gas extension of threshold logic with adaptive calibration	Develop multi-parameter FHI from single-gas baseline
5	Suyatno & Hisam (2010)	Scalable threshold alerting architecture	Apply adaptive logic to multi-scale deployment
6	Rifai et al. (2025)	Messaging app integration for rapid crew notification	Embed in FHI output layer for decision-support interface
7	Subono et al. (2018)	Zigbee WSN for enclosed hostile environments	Adapt for cargo hold spatial sensor grid design
8	Yusuf et al. (2023)	IoT alerting with remote monitoring capability	Extend with multi-sensor fusion and adaptive thresholds
9	Pangestu et al. (2025)	Risk classification methodology transferable to maritime logistics	Integrate operational context (cargo manifest) into FHI weighting
10	Wibowo et al. (2024)	UAV hazard zoning for visual risk representation	Adapt for 3D cargo hold risk visualization
11	Maulana & Khomsin (2017)	Data-driven site characterization methodology	Apply to sensor placement optimization in cargo holds

12	Kasmira (2025)	Multi-sensor integration with measurable safety outcomes	Strongest operational analogue; direct model for maritime validation protocol
13	Ikhsan & Rivai (2020)	Long-range IoT monitoring with environmental sensitivity	Incorporate LoRa architecture into distributed cargo hold sensor network
14	Purnama et al. (2025)	Agile cloud-based IoT detection development	Apply rapid prototyping approach to maritime FHI system iteration
15	Pratama & Basuki (2022)	FMEA risk prioritization for maritime maintenance contexts	Integrate FMEA-derived failure modes into FHI threshold calibration

Research Trends

A clear and consistent trend emerges across the reviewed literature: the field is moving from reactive, single-sensor alerting systems toward proactive, multi-sensor adaptive systems capable of continuous risk assessment. This transition is driven by three converging forces — advances in low-cost IoT sensor hardware, availability of edge-computing platforms capable of running lightweight machine learning inference, and increasing regulatory pressure from IMO and classification societies for more reliable fire safety performance documentation.

Critically, however, this technological momentum has not yet translated into equivalent advances in maritime-specific validation. The gap between what can be prototyped in a laboratory and what has been demonstrated to perform reliably in a cargo hold remains wide. This suggests that the field's next phase of progress is not primarily a technical problem but a validation and standardization problem — requiring coordinated research infrastructure, shared datasets, and collaborative trials rather than additional novel algorithm proposals.

Discussion

The synthesis of findings reveals both the promise and the significant remaining limitations of adaptive fire detection research for maritime cargo holds. While adaptive thresholding approaches — particularly Bayesian updating and statistical control charts — demonstrably outperform static thresholds under variable environmental conditions, the evidence base for this conclusion is built almost entirely on controlled experiments rather than operational deployments. This matters because controlled experiments, by design, reduce the complexity and variability that adaptive systems are intended to address; demonstrating performance gains under simplified conditions provides weak evidence for real-world effectiveness.

A further concern is the overrepresentation of Indonesian local-context studies in the reviewed literature. While these studies collectively represent a valuable and growing body of work on IoT-based detection prototyping, they predominantly employ low-cost consumer-grade sensors (MQ-series) with known limitations in drift, cross-sensitivity, and long-term reliability under maritime conditions. International literature, by contrast, has developed more rigorous sensor calibration methodologies and standardized performance benchmarks (Zhang et al., 2021; Ko et al., 2022; Verstockt et al., 2010), and the field would benefit from closer integration between these complementary research traditions.

The practical implications are clear. For a maritime institution or shipbuilder seeking to deploy an adaptive fire detection system today, the current literature offers useful design principles — multi-sensor integration, probabilistic fusion, FHI risk scoring — but insufficient validated specifications. The development of standardized testing protocols, open benchmark datasets, and maritime-context performance metrics represents the most impactful near-term contribution that the research community can make.

CONCLUSION

This PRISMA-based systematic review synthesized 20 empirical and simulation-based studies to examine adaptive thresholding and Fire Hazard Index (FHI) frameworks for early fire detection in ship cargo holds, responding to three specific research questions on methodology, design, and research gaps.

Main Findings. The evidence confirms that adaptive thresholding approaches — particularly probabilistic sensor fusion methods (Bayesian inference, Dempster–Shafer theory) combined with machine learning classifiers (SVM, Random Forest) and statistical control techniques (CUSUM, EWMA) — consistently outperform static-threshold systems in controlled conditions, achieving reported false alarm reductions of 30–50% and faster detection response. However, fewer than 20% of reviewed studies were validated in real maritime environments, and no standardized maritime FHI framework exists for regulatory adoption. The majority of studies rely on single-gas, static-threshold designs, indicating a persistent gap between theoretical capability and implemented practice.

Scientific Contribution. This review makes three distinct contributions. First, it provides the first systematic, PRISMA-guided synthesis of adaptive fire detection literature with explicit attention to maritime cargo hold transferability. Second, it identifies and substantiates five concrete research gaps — maritime validation absence, FHI non-standardization, single-sensor dominance, dataset scarcity, and suppression system decoupling — that define the field's primary development barriers. Third, it proposes a three-layer adaptive maritime fire detection framework (Sensor Layer → Adaptive Engine → FHI Output Layer) as a conceptual architecture for integrating existing methodological advances into a coherent, deployable system design.

Practical Implications. For maritime safety practitioners, classification societies, and shipboard system designers, this review indicates that the core components of effective adaptive fire detection — multi-sensor IoT integration, probabilistic data fusion, dynamic risk scoring — are technically mature and available for implementation. The primary barrier to deployment is not technological but institutional: the absence of standardized performance benchmarks, certified testing protocols, and validated reference datasets. Collaboration between maritime research institutions, sensor manufacturers, and international safety regulators (IMO, SOLAS) is therefore the most urgent practical need.

Directions for Further Research. Future studies should prioritize: (1) large-scale field trials in operational cargo hold environments across diverse vessel types and cargo categories; (2) development of open, annotated benchmark datasets for cargo hold fire detection under varying conditions; (3) design and regulatory validation of a standardized maritime FHI framework with defined sensor specifications and performance thresholds; (4) development of computationally efficient hybrid physical–machine learning models suitable for edge deployment on constrained onboard hardware; and (5) integration of adaptive detection systems with automated suppression and ventilation control to enable end-to-end fire safety response evaluation.

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