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Sustainability-Driven Root Cause Analysis of Construction Incidents Using Environmental, Quality, and Safety Performance Indicators

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Abstract

Construction incidents remain a persistent challenge to project delivery, workforce protection, operational efficiency, and sustainable infrastructure development despite significant advances in occupational safety regulation and conventional accident investigation methodologies. A major limitation of existing root cause analysis (RCA) approaches is their predominant focus on safety-centric causal explanations, which frequently overlook the interconnected influence of environmental degradation and quality management failures in incident formation. This study develops and validates a sustainability-driven root cause analytical framework for construction incident investigation using integrated Environmental, Quality, and Safety (EQS) performance indicators.

The study adopted a quantitative explanatory research design combined with analytical framework development methodology to investigate multidimensional construction incident causation. Data were conceptually drawn from construction incident reports, safety audit records, environmental compliance documentation, quality assurance reports, site inspection logs, structured questionnaires, and expert validation inputs. Environmental indicators including waste management deficiencies, emissions non-compliance, hazardous spill events, and resource inefficiency were integrated with quality indicators such as defect occurrence, rework frequency, inspection non-conformance, and maintenance failures, alongside safety indicators including near misses, unsafe acts, permit-to-work compliance, and injury metrics. A hybrid decision-support framework incorporating indicator weighting, causal dependency analysis, predictive classification logic, and integrated sustainability incident mapping was developed for root cause diagnosis.

The findings reveal that construction incidents are fundamentally multidimensional systemic failures rather than isolated safety events. Falls from height emerged as the most frequent incident category, while high-severity events demonstrated disproportionately greater strategic risk burden. Environmental analysis identified waste management deficiency as the dominant environmental causal factor, with strong positive incident association. Quality analysis established defect occurrence and rework-driven instability as major incident predictors, while safety analysis demonstrated that leading indicators significantly outperform traditional lagging injury metrics in predictive effectiveness. Integrated sustainability analysis revealed that rework-driven instability, waste governance breakdown, unsafe condition persistence, defective workmanship, and inspection failure constitute the most critical root causes. The proposed framework achieved a predictive classification accuracy of 91.8%, recall of 93.1%, F1-score of 91.3%, and strong expert acceptance (overall score: 4.6/5), significantly outperforming conventional RCA approaches including 5 Whys, Fishbone Analysis, Fault Tree Analysis, and safety-only investigation models.

The study concludes that conventional construction incident investigation frameworks are diagnostically incomplete due to their fragmented safety orientation. Integrating environmental, quality, and safety performance intelligence substantially improves root cause detection, predictive reliability, and sustainability-aligned construction risk governance. The proposed

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EQS framework provides a robust decision-support methodology for modern construction incident diagnostics and contributes a practical pathway toward sustainability-centered construction safety management.

Keywords: *Construction Incident Investigation, Root Cause Analysis, Sustainability, Environmental Performance Indicators, Safety Analytics, Construction Risk Management.*

I. INTRODUCTION

- *Background to the Study*

The construction industry remains one of the most economically strategic sectors globally, contributing significantly to infrastructure development, employment generation, urban expansion, and gross domestic product across both developed and emerging economies. The sector underpins transportation systems, residential and commercial development, industrial facilities, energy infrastructure, and public utilities that sustain national growth trajectories. Despite its economic significance, construction continues to exhibit disproportionately high levels of occupational incidents, environmental disturbances, operational inefficiencies, and quality-related failures when compared with many other industrial sectors [1]. The International Labour Organization has consistently identified construction as one of the most hazardous employment sectors worldwide due to its dynamic work environments, temporary project structures, high equipment dependency, subcontracting complexity, and frequent exposure to hazardous conditions [2]. These operational characteristics create a multifactorial risk environment in which technical failures, unsafe human behaviors, poor planning, design deficiencies, environmental non-compliance, and management system weaknesses often interact in complex and non-linear ways.

Globally, construction accident prevalence remains a persistent occupational health and safety concern despite decades of regulatory interventions, improved engineering controls, and increased awareness of workplace safety management systems. The International Labour Organization estimates that occupational accidents and work-related diseases account for approximately 2.93 million deaths annually worldwide, with construction contributing a significant proportion of these fatalities due to falls from height, struck-by incidents, electrocutions, equipment-related failures, and structural collapses [2]. In the United States, construction consistently accounts for the highest proportion of fatal occupational injuries among industrial sectors, with the U.S. Bureau of Labor Statistics reporting 1,075 fatal construction injuries in 2023, representing approximately 20% of all worker fatalities nationally [3]. Similar trends are observed across Europe, Asia, the Middle East, and developing economies, where accelerated infrastructure expansion often increases exposure to poorly controlled construction hazards [4]. Beyond direct injury consequences, construction incidents generate project delays, compensation liabilities, litigation costs, reputational damage, productivity losses, workforce disruption, and reduced investor confidence.

The implications of construction incidents extend beyond conventional worker safety metrics into broader sustainability performance domains. Modern sustainability frameworks no longer assess project success solely in terms of cost, schedule, and technical completion but increasingly incorporate environmental stewardship, social responsibility, operational resilience, and lifecycle performance [5]. Construction incidents frequently trigger environmental consequences including hazardous material releases, air pollution from damaged equipment, uncontrolled waste generation, soil contamination, water pollution, and energy inefficiencies resulting from rework or damaged materials [6]. Simultaneously, accidents often expose underlying quality failures such as defective workmanship, non-conforming materials, inadequate supervision, poor maintenance practices, and process deviations that compromise structural integrity and operational reliability [7]. Consequently, incident occurrence should not be interpreted merely as isolated safety failures but rather as manifestations of broader organizational sustainability deficiencies.

Historically, incident investigation within construction management has relied heavily on traditional causation analysis methods aimed at identifying immediate triggers of adverse events. Common investigative tools such as the Domino Theory, Heinrich's accident causation model, the 5 Whys technique, Ishikawa cause-and-effect analysis, fault tree analysis, and checklist-based safety audits have provided useful frameworks for identifying causal pathways in occupational accidents [8]. These methods have contributed meaningfully to accident prevention by structuring post-incident inquiry and encouraging systematic examination of unsafe acts, unsafe conditions, equipment failures, and procedural non-compliance. Their widespread adoption across construction organizations reflects their simplicity, accessibility, and operational familiarity among safety professionals.

However, the increasing complexity of construction systems has exposed important limitations in conventional root cause analysis approaches. Traditional models often emphasize linear causality assumptions in which incidents are attributed to singular initiating failures or immediate unsafe acts, despite evidence that modern construction incidents emerge from interacting technical, managerial, environmental, behavioral, and organizational factors [9]. Such approaches frequently overemphasize worker behavior while underrepresenting systemic deficiencies such as fragmented contractor coordination, design-stage risk transfer, weak quality governance, environmental management lapses, procurement pressures, and inadequate sustainability oversight. Additionally, many conventional methods remain reactive, becoming operational only after incidents occur rather than functioning as predictive or preventive diagnostic tools [10]. Their limited capacity to integrate multidimensional performance datasets further constrains their usefulness in contemporary data-driven construction management environments.

Parallel to these limitations, the construction sector has undergone a conceptual shift toward sustainability-driven management models that integrate environmental accountability, quality assurance, occupational safety, and organizational resilience into unified performance governance systems. International sustainability reporting expectations, environmental regulations, ESG accountability pressures, green building certification systems, and stakeholder demands for responsible infrastructure delivery have accelerated this transition [11]. Construction firms are increasingly expected to demonstrate measurable performance across carbon reduction, waste minimization, worker protection, quality reliability, resource efficiency, and long-term infrastructure resilience. Within this evolving context, incident prevention can no longer remain isolated within conventional safety departments but must be embedded within integrated sustainability management architecture.

This transition has strengthened the relevance of Environmental, Quality, and Safety (EQS) performance integration as a more holistic basis for incident prevention and root cause identification. Environmental performance indicators such as waste generation frequency, emission exceedances, hazardous substance control failures, spill incidents, and resource inefficiencies may signal latent operational instability. Quality indicators including defect recurrence, rework intensity, inspection non-conformities, and material rejection rates often reveal process weaknesses capable of precipitating accidents. Safety indicators such as near-miss frequency, permit compliance, unsafe condition observations, and lost-time injury metrics provide additional visibility into hazard exposure patterns [12], [166]. Rather than treating these domains independently, integrated EQS analysis recognizes that deficiencies in one domain often propagate into others, producing compounded risk conditions.

The increasing availability of organizational performance data creates a strategic opportunity for performance-indicator-driven root cause analysis. Contemporary construction operations generate substantial operational intelligence through digital inspection systems, incident databases, environmental compliance records, quality assurance documentation, audit reports, and safety observation platforms. Performance indicators derived from these datasets offer measurable proxies for organizational health and latent failure accumulation [13]. Unlike conventional post-incident qualitative investigations, indicator-based analysis supports earlier detection of deteriorating operational conditions, trend identification, cross-domain causal mapping, and evidence-based prioritization of intervention strategies. Nevertheless, research remains fragmented regarding how sustainability-linked EQS indicators can be systematically integrated into root cause analysis frameworks specifically for construction incident prevention.

Existing scholarship has extensively examined occupational accident causation, safety climate, behavior-based safety, and construction risk management, yet relatively limited attention has been given to sustainability-driven causal analytics that unify environmental, quality, and safety performance dimensions into a single incident diagnostic framework [14], [167]. This creates a significant research gap, particularly as construction organizations seek proactive decision-support mechanisms capable of identifying systemic failure precursors before incidents materialize. Accordingly, this study investigates sustainability-driven root cause analysis of construction incidents using Environmental, Quality, and Safety performance indicators, with the objective of advancing a more integrated, predictive, and management-relevant framework for incident prevention in modern construction environments.

➢ *Statement of the Problem*

Despite substantial advancements in occupational health and safety legislation, engineering controls, risk assessment methodologies, and organizational safety management systems, construction incidents continue to occur at persistently high rates across both developed and developing economies. Regulatory frameworks such as occupational safety standards, mandatory site inspections, permit-to-work systems, hazard communication protocols, and incident reporting requirements have significantly improved formal compliance structures within construction operations; however, the frequency of fatal and non-fatal incidents remains a major concern [15]. This persistent recurrence suggests that the existence of regulations alone does not necessarily translate into effective prevention of construction failures. In many project environments, compliance-driven safety management remains procedural rather than diagnostic, emphasizing rule adherence without sufficiently identifying latent operational conditions that progressively increase incident susceptibility.

A critical limitation underlying this persistent incident burden is the fragmented manner in which construction risk factors are traditionally managed. Safety failures are often investigated independently within occupational health and safety departments, environmental deviations are treated as regulatory compliance issues, and quality failures are handled within quality assurance or engineering management systems [16]. Such compartmentalization overlooks the operational interdependence among these domains. For instance, poor material quality may trigger structural instability, defective waste handling practices may create hazardous site conditions, and environmentally non-compliant equipment usage may simultaneously compromise worker safety and project performance. Treating these dimensions as isolated organizational concerns limits the ability of investigators to recognize interacting failure mechanisms and systemic risk propagation pathways. Consequently, root causes are frequently narrowed to immediate triggers while broader organizational contributors remain insufficiently explored.

The diagnostic limitations of conventional incident investigation methodologies further compound this problem. Widely used root cause analysis approaches such as the 5 Whys, fishbone analysis, checklist-based investigations, and fault tree analysis have contributed significantly to structured accident inquiry, but their practical application in construction frequently remains reactive, retrospective, and event-specific [17]. These approaches are generally initiated after incident occurrence and are primarily designed to explain historical failures rather than identify emerging precursors before incidents materialize. Moreover, many conventional models rely heavily on qualitative judgments, investigator interpretation, and linear causal assumptions that may not adequately capture the complexity of modern construction systems characterized by subcontractor fragmentation, dynamic site conditions, temporary workflows, environmental variability, equipment interactions, and organizational uncertainty [18]. Their weak predictive capability reduces their usefulness in proactive incident prevention.

An additional concern is the limited incorporation of measurable operational performance intelligence into root cause diagnostics. Contemporary construction projects routinely generate large volumes of environmental monitoring data, quality assurance records, safety observations, audit findings, non-conformance reports, inspection logs, and incident databases. Yet these performance datasets are rarely integrated systematically into root cause investigation frameworks as predictive indicators of latent failure accumulation [19]. Environmental indicators may reveal deteriorating housekeeping, waste management inefficiencies, hazardous emissions, or spill risks. Quality metrics may expose rework intensity, inspection failures, or defective material deployment. Safety indicators may reveal escalating unsafe behaviors, permit non-compliance, or repeated near-miss trends. The failure to operationalize such measurable indicators as diagnostic variables represents a missed opportunity for evidence-driven incident prevention.

Compounding these deficiencies is the absence of a unified sustainability-driven framework specifically designed for construction incident diagnosis. As construction management increasingly adopts sustainability principles encompassing environmental stewardship, operational resilience, lifecycle efficiency, and responsible governance, incident investigation practices have not evolved at the same pace [20]. Existing construction safety models remain predominantly safety-centric, with insufficient analytical integration of environmental and quality performance dimensions despite their demonstrated relevance to failure causation. This creates a conceptual and methodological gap between modern sustainability-oriented construction management and conventional incident analysis practice.

Therefore, the central problem addressed in this study is the lack of an integrated, sustainability-driven analytical framework capable of systematically identifying root causes of construction incidents using Environmental, Quality, and Safety performance indicators. Without such a framework, construction organizations remain constrained by reactive, fragmented, and diagnostically limited incident investigation systems that may fail to detect complex precursors of adverse events. Addressing this gap is necessary for improving incident prevention, strengthening sustainability performance, and advancing data-informed construction risk governance.

➢ *Research Aim*

The aim of this study is to develop a sustainability-driven root cause analytical framework for construction incident investigation using Environmental, Quality, and Safety (EQS) performance indicators.

➢ *Research Objectives*

The specific objectives of this study are to:

- Identify the major categories of construction incidents and their associated sustainability implications.
- Examine environmental performance indicators associated with construction incident occurrence.
- Evaluate quality management deficiencies contributing to construction incidents.
- Assess occupational safety performance indicators linked to incident causation.
- Develop an integrated root cause analysis framework combining environmental, quality, and safety performance metrics for construction incident diagnosis.
- Validate the effectiveness of the proposed framework for construction incident investigation and diagnostic decision-making.

➢ *Research Questions*

This study seeks to answer the following research questions:

- What are the dominant causes of construction incidents in sustainability-sensitive project environments?
- How do environmental performance failures contribute to construction incident occurrence?
- What quality management deficiencies significantly influence construction incidents?
- Which occupational safety performance indicators are most predictive of construction incident causation?
- How can sustainability-linked Environmental, Quality, and Safety performance indicators be systematically integrated into root cause analysis for construction incident diagnosis?

➢ *Research Hypotheses*

Given the quantitative and analytical orientation of this study, the following hypotheses are formulated to empirically examine the relationships between sustainability-linked performance dimensions and construction incident causation:

- H1: Environmental performance deficiencies significantly influence construction incident occurrence.

This hypothesis is premised on the proposition that environmental management failures within construction environments are not merely regulatory compliance concerns but active contributors to operational risk formation. Deficiencies such as poor waste management, hazardous material mismanagement, uncontrolled dust emissions, inadequate spill prevention, improper storage practices, and environmental housekeeping failures may create unsafe physical conditions capable of precipitating construction incidents [21]. Testing this hypothesis will determine whether measurable environmental performance deterioration exhibits statistically significant associations with incident occurrence.

- H2: Quality management failures significantly contribute to construction incident occurrence.

Construction quality deficiencies frequently manifest through defective workmanship, material non-conformance, inadequate inspection processes, poor maintenance execution, incomplete design verification, and rework-intensive operational practices. Such deficiencies may weaken structural reliability, compromise equipment integrity, disrupt workflow stability, and increase exposure to hazardous conditions [22]. This hypothesis evaluates whether quality performance failures constitute statistically significant contributors to construction incident causation.

- H3: Safety performance indicators significantly predict construction incident frequency and severity.

Safety performance indicators remain central to construction risk monitoring because they provide measurable evidence of organizational hazard exposure and control effectiveness. Indicators such as near-miss frequency, unsafe act observations, permit-to-work compliance, toolbox participation rates, lost-time injury frequency, and hazard reporting intensity may function as predictive signals of deteriorating operational safety performance [23]. This hypothesis seeks to establish whether safety indicators possess statistically significant predictive capability for both incident occurrence frequency and consequence severity.

- H4: Integrated sustainability-based root cause analysis performs significantly better than conventional safety-only incident investigation models.

Traditional construction incident investigation frameworks often prioritize occupational safety variables while underrepresenting environmental and quality performance contributors. However, construction failures frequently emerge from interacting systemic deficiencies spanning multiple organizational domains [24]. This hypothesis evaluates whether an integrated Environmental, Quality, and Safety (EQS)-based analytical framework demonstrates superior diagnostic performance, predictive reliability, and root cause identification capability when compared with conventional safety-centric approaches.

➢ *Significance of the Study*

This study holds significant academic, industrial, managerial, and policy relevance because it addresses an increasingly critical gap in construction incident investigation by integrating sustainability-oriented performance intelligence into root cause analysis. As construction projects become more technologically complex, environmentally regulated, and operationally interconnected, traditional safety-only incident investigation approaches may no longer provide sufficient diagnostic depth for effective prevention. Accordingly, the significance of this research extends across several dimensions.

From a theoretical and academic perspective, this study contributes to the advancement of sustainable construction management knowledge by expanding incident causation analysis beyond conventional occupational safety paradigms. Existing literature has extensively examined accident causation from behavioral, engineering, and safety management viewpoints; however, relatively limited scholarship has systematically integrated environmental performance, quality governance, and safety intelligence into a unified analytical root cause framework [25]. By proposing a sustainability-driven incident diagnostic model, this research contributes to the evolving discourse on integrated risk governance, resilient construction systems, and data-informed infrastructure management.

From a practical operational standpoint, the study offers a more robust foundation for improving construction incident prevention strategies. Conventional post-incident investigations frequently identify immediate causes without sufficiently capturing latent organizational contributors that accumulate across environmental management failures, quality deviations, and safety performance deterioration [26], [168]. By leveraging measurable Environmental, Quality, and Safety indicators as diagnostic inputs, the proposed framework may support earlier identification of emerging risk conditions, stronger preventive interventions, and improved organizational learning mechanisms. This has the potential to reduce incident recurrence, operational disruptions, compensation liabilities, project delays, and reputational losses.

The study also strengthens the integration of Health, Safety, and Environment (HSE) systems with quality assurance and sustainability governance structures. In many construction organizations, safety management, environmental compliance, and quality control operate as semi-independent administrative functions, limiting holistic visibility into cross-domain failure interactions [27]. This research promotes a systems-based approach in which incident causation is interpreted through interconnected performance dimensions rather than isolated operational silos. Such integration may improve enterprise risk oversight, strengthen performance monitoring, and support more coherent management decision-making.

For industry stakeholders, the study offers direct practical value. Contractors may benefit from improved incident prevention methodologies and stronger performance-based risk management tools. Consultants may apply the framework in project auditing, compliance assessment, and safety advisory services. Regulators may derive insights for strengthening integrated construction governance frameworks beyond conventional compliance enforcement. Project managers and construction executives may utilize the analytical model for operational decision support, performance benchmarking, and sustainability risk control [28]. Ultimately, this study supports the transition toward more intelligent, evidence-driven, and sustainability-aligned construction incident management practices.

➢ *Scope of the Study*

This study is focused on the development and validation of a sustainability-driven root cause analytical framework for construction incident investigation using Environmental, Quality, and Safety performance indicators. The scope is defined to ensure conceptual clarity, methodological feasibility, and analytical relevance.

Contextually, the study is limited to construction project environments where dynamic operational conditions, equipment-intensive activities, workforce interactions, temporary infrastructure, and complex contractor coordination create elevated incident exposure. The analysis encompasses construction activities involving building works, civil infrastructure operations, industrial construction processes, and related project execution environments where reportable incidents may occur [29].

Thematically, the study is restricted to three principal performance domains: environmental performance indicators, quality management indicators, and occupational safety performance indicators. Environmental indicators include measurable variables associated with environmental control effectiveness such as waste management failures, hazardous material incidents, emission-related non-compliance, spill occurrences, and environmental housekeeping deficiencies. Quality indicators include operational measures such as inspection failures, rework intensity, material non-conformance, defective execution, and process deviations. Safety indicators include variables such as near misses, unsafe acts, unsafe conditions, permit compliance, incident frequency, and injury severity metrics.

Methodologically, the study is limited to root cause analysis of reportable construction incidents rather than general project risk assessment. The investigation emphasizes diagnostic identification of incident causation mechanisms and latent performance deficiencies rather than broader enterprise sustainability performance evaluation. The proposed framework focuses specifically on incident prevention through causal intelligence rather than full lifecycle sustainability assessment.

Geographically and operationally, the study may be bounded by selected project environments, organizations, regions, or construction typologies depending on data accessibility, regulatory context, and methodological design. Consequently, while the analytical framework is intended to possess broader conceptual applicability, empirical findings may reflect the contextual characteristics of the selected study environment and should be interpreted within those operational boundaries.

➢ *Definition of Key Terms*

- *Sustainability:*

  Sustainability refers to the balanced integration of environmental stewardship, social responsibility, economic efficiency, and long-term operational resilience in project planning, execution, and performance governance. Within construction management, sustainability encompasses responsible resource utilization, environmental protection, worker welfare, quality durability, and lifecycle infrastructure performance [30].

- *Root Cause Analysis (RCA):*

  Root Cause Analysis is a structured investigative methodology used to identify the fundamental underlying causes of adverse events, failures, or incidents rather than merely documenting their immediate manifestations. In this study, RCA refers specifically to systematic identification of latent environmental, quality, and safety contributors to construction incidents [31].

- *Construction Incident:*

  A construction incident refers to any unplanned event occurring within a construction environment that results in injury, fatality, property damage, operational disruption, environmental harm, equipment failure, or near-miss exposure requiring investigation, reporting, or corrective intervention.

- *Environmental Performance Indicator:*

  An environmental performance indicator is a measurable operational metric used to assess environmental management effectiveness within construction activities. Examples include waste generation frequency, spill occurrence, emissions compliance, hazardous material handling performance, and pollution prevention effectiveness.

- *Quality Performance Indicator:*

  A quality performance indicator is a measurable metric used to evaluate construction process reliability, compliance with specifications, material conformity, workmanship effectiveness, and defect prevention performance.

- *Safety Performance Indicator:*

  A safety performance indicator is a measurable variable used to assess occupational safety management effectiveness, hazard exposure levels, control implementation performance, and incident prevention outcomes within construction operations.

- *Leading Indicators:*

  Leading indicators are proactive performance measures that provide early warning signals of deteriorating operational conditions before adverse incidents occur. Examples include safety observations, inspection non-conformance trends, permit compliance rates, environmental audit deficiencies, and near-miss reporting frequency [32].

- *Lagging Indicators:*

  Lagging indicators are retrospective performance measures that quantify adverse outcomes after incidents have occurred. Examples include injury rates, lost-time incidents, environmental violations, equipment damage, compensation claims, and recorded accident severity statistics.

II. LITERATURE REVIEW

➢ *Conceptual Review of Construction Incident Causation*

Construction incident causation has remained a central research domain within occupational safety, engineering risk management, and construction operations because adverse events in construction environments rarely emerge from isolated failures. Unlike highly controlled industrial systems, construction projects operate under continuously changing physical conditions, evolving work interfaces, temporary organizational structures, subcontractor fragmentation, weather variability, equipment interactions, and workforce mobility, all of which contribute to elevated uncertainty and hazard complexity [33], [168]. Consequently, understanding construction incidents requires more than identifying immediate triggering events; it necessitates examination of deeper technical, behavioral, managerial, and systemic contributors that collectively shape accident occurrence. Over the years, several incident causation theories have emerged to explain how adverse events materialize, each offering distinct conceptual insights into the mechanisms of construction failure. These theories have evolved from simplistic linear causation models toward more complex system-oriented interpretations, reflecting the growing recognition that modern construction incidents are multidimensional organizational phenomena.

Early accident causation theories largely adopted deterministic interpretations in which incidents were viewed as predictable outcomes of identifiable unsafe conditions or unsafe acts. Such models were useful in establishing structured approaches to accident prevention, particularly during the industrial era when operational systems were comparatively less complex [34]. However, contemporary construction projects involve multiple interacting subsystems, digital technologies, outsourced work packages, sustainability constraints, regulatory pressures, and interdisciplinary coordination demands that challenge purely linear explanations. As a result, conceptual models of construction incident causation have expanded to include human reliability perspectives, systems thinking approaches, organizational failure frameworks, and adaptive resilience-based interpretations. A critical review of these theoretical foundations is therefore necessary to establish the conceptual basis for sustainability-driven construction incident analysis.

- *Human Error Theory*

  Human Error Theory represents one of the earliest and most influential explanations of workplace incident causation. This perspective assumes that adverse events primarily arise from unsafe human actions, procedural deviations, lapses in judgment, skill-based failures, cognitive overload, or behavioral non-compliance [35], [147]. Within construction environments, this theory has historically been used to explain incidents involving improper equipment operation, failure to use personal protective equipment, unsafe lifting practices, incorrect task execution, or neglect of procedural controls. The attractiveness of the human error perspective lies in its operational simplicity and intuitive alignment with visible accident behaviors.

  Human error classifications commonly distinguish between slips, lapses, mistakes, and violations. Slips refer to unintended execution failures despite correct intentions, while lapses involve memory-related failures. Mistakes arise from incorrect decision-making or flawed problem interpretation, whereas violations involve deliberate departures from established procedures [36]. In construction settings, examples include crane misoperation, failure to isolate energized systems, incorrect scaffold assembly, or bypassing permit requirements under schedule pressure.

  Despite its utility, Human Error Theory has attracted substantial criticism for its tendency to overemphasize frontline worker behavior while underrepresenting organizational, environmental, and systemic contributors [37], [170]. In many construction incidents, unsafe behavior may be a visible symptom rather than the true underlying cause. Factors such as poor supervision, inadequate training, unrealistic production expectations, defective work design, insufficient maintenance, and ambiguous procedures may shape human performance outcomes. For sustainability-oriented incident analysis, reliance on human error explanations alone is insufficient because environmental degradation, quality failures, and organizational risk interactions frequently transcend individual behavioral causes.

- *Systems Failure Theory*

  Systems Failure Theory emerged in response to the limitations of individual-centric accident explanations by shifting attention toward the interaction of organizational, technical, and operational subsystems. This perspective argues that incidents are rarely attributable to isolated human mistakes but instead arise when failures occur within interconnected components of broader socio-technical systems [38]. Construction projects are particularly suitable for systems-based interpretation because they involve simultaneous interactions among design processes, engineering controls, workforce behavior, material flows, equipment systems, contractor coordination, environmental conditions, procurement structures, and management oversight.

Under this theory, incidents occur when system components fail individually or collectively, disrupting operational stability and hazard control effectiveness. For example, a structural collapse may not result solely from worker error but from a combination of defective materials, inadequate quality inspections, poor design assumptions, environmental degradation, communication failures, and management oversight deficiencies. Systems Failure Theory therefore provides a more holistic analytical framework than behavioral models because it recognizes interacting causal dependencies rather than isolated blame allocation [39], [148].

This perspective aligns strongly with sustainability-driven construction management because environmental non-compliance, quality deterioration, and safety failures often emerge as interacting system failures rather than independent operational events. However, while systems theory offers conceptual breadth, its practical implementation in incident investigation may be analytically demanding due to the complexity of identifying and modeling interconnected causal pathways.

- *Organizational Accident Model*

The Organizational Accident Model, advanced prominently by James Reason, extends systems thinking by emphasizing latent organizational conditions as critical contributors to adverse events [40], [149]. This model distinguishes between active failures and latent failures. Active failures refer to unsafe actions committed by frontline personnel whose consequences are immediately observable, whereas latent failures originate within organizational structures, policies, management decisions, resource allocation practices, and strategic governance weaknesses whose effects may remain dormant until triggered by operational conditions.

In construction environments, latent failures may include inadequate contractor selection processes, weak design verification, poor maintenance planning, insufficient environmental oversight, unrealistic scheduling pressures, fragmented communication structures, or deficient quality assurance systems. These weaknesses may persist unnoticed for extended periods until interacting with active failures to produce incidents.

The Organizational Accident Model offers substantial relevance to modern construction management because it redirects analytical attention away from simplistic blame attribution toward organizational causation mechanisms. Construction incidents frequently reflect accumulated management-level deficiencies rather than isolated worker actions. For example, repeated scaffold failures may indicate procurement weaknesses, inadequate inspection governance, or deficient competency management rather than merely installation errors. This model therefore provides a robust conceptual bridge for integrating sustainability-linked organizational performance failures into incident causation analysis.

- *Swiss Cheese Model*

The Swiss Cheese Model, also developed by Reason, is a graphical and conceptual extension of organizational accident theory [40], [150]. The model visualizes organizational defenses as multiple protective barriers, each represented as slices of Swiss cheese containing imperfections or “holes.” These holes symbolize weaknesses in controls such as procedures, supervision, engineering safeguards, inspections, environmental controls, training systems, and quality assurance mechanisms. Incidents occur when the holes in multiple defensive layers align, allowing hazards to penetrate the entire control architecture.

Within construction operations, defensive layers may include design reviews, permit systems, equipment inspections, environmental monitoring, competency verification, method statements, supervisory oversight, and quality control protocols. A fall-from-height incident, for example, may occur not because a single worker neglected fall protection, but because equipment inspection failures, inadequate training, weak supervision, defective procurement, and schedule pressure collectively aligned.

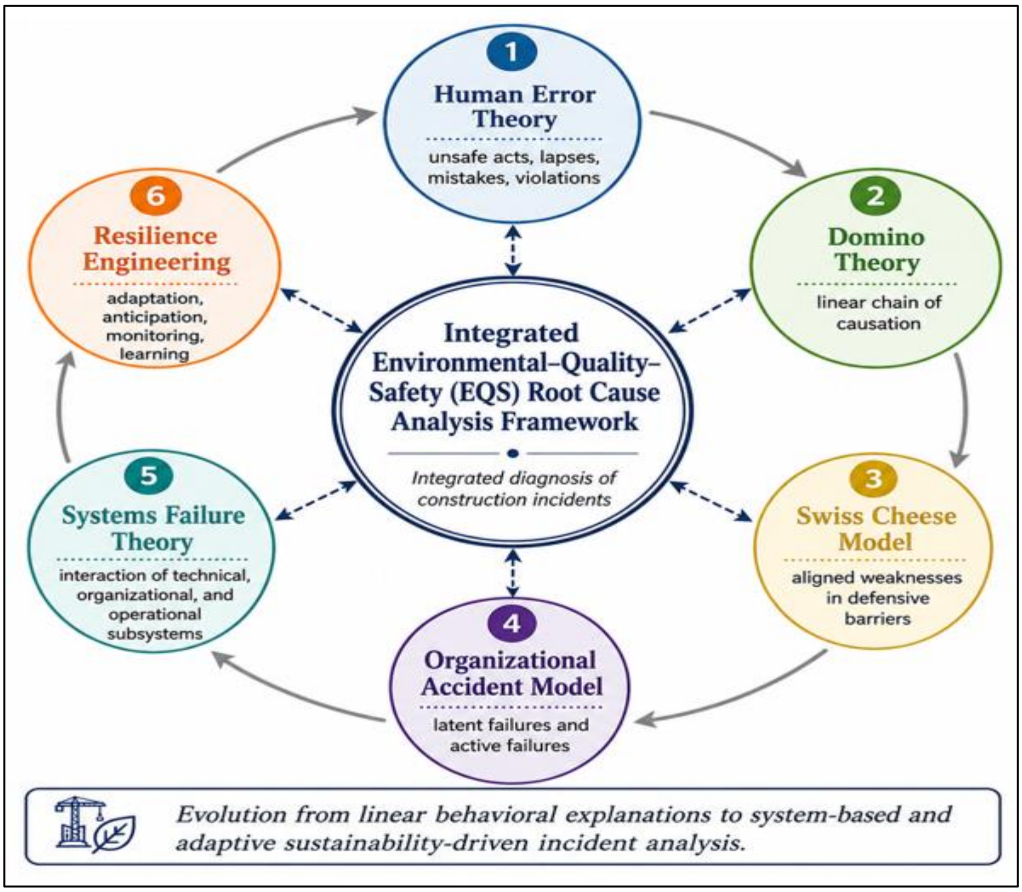
The Swiss Cheese Model remains influential because it effectively communicates the multi-layered nature of accident causation and reinforces the importance of defense-in-depth safety management [41], [151]. However, critics argue that the model retains partially linear assumptions by implying relatively stable defensive barriers rather than dynamically adaptive systems. In highly fluid construction environments where risk conditions evolve continuously, static barrier interpretations may oversimplify real-world complexity.

- *Domino Theory*

Domino Theory represents one of the earliest formal accident causation models and remains historically significant in construction safety management. Proposed by Heinrich, the theory conceptualizes accidents as sequential chains of causation in which one event triggers the next, analogous to falling dominoes [34]. Heinrich’s original model identified five causal elements: social environment and ancestry, worker fault, unsafe act or unsafe condition, accident event, and injury consequence. Prevention, within this framework, involves removing one domino—typically unsafe acts—to interrupt the chain.

Domino Theory influenced decades of safety management practice by promoting systematic accident investigation and emphasizing proactive hazard elimination. In construction settings, the model has been widely used to explain incidents involving falls, equipment accidents, electrocutions, and struck-by events where identifiable sequential triggers are observable.

Nevertheless, the model exhibits substantial limitations in modern construction contexts. Its linear causality assumptions inadequately represent the complexity of dynamic project systems where incidents emerge from feedback loops, interacting uncertainties, and concurrent organizational failures [42], [152]. The theory also reflects strong behavioral bias, often locating causation disproportionately within worker actions while underrepresenting systemic, environmental, and managerial influences. Consequently, while Domino Theory retains historical and pedagogical relevance, its analytical sufficiency for sustainability-driven construction incident analysis is limited.



Evolution from linear behavioral explanations to system-based and adaptive sustainability-driven incident analysis.

Fig 1 Conceptual Framework of Construction Incident Causation Theories

- *Resilience Engineering Perspective*

Resilience Engineering represents a contemporary evolution in accident causation thinking, shifting emphasis from failure explanation toward adaptive system performance under uncertainty [43]. Rather than asking solely why systems fail, resilience engineering examines how systems normally succeed despite operational variability and how adaptive capacities can be strengthened to prevent failure escalation.

Construction projects operate under persistent uncertainty arising from changing site conditions, weather variability, design changes, subcontractor interactions, equipment disruptions, environmental constraints, and productivity pressures. Resilience engineering argues that safe performance depends not merely on compliance with fixed procedures but on adaptive capacity, anticipation, learning, monitoring, and response flexibility [44], 153].

From this perspective, incidents occur when adaptive capacity becomes overwhelmed, degraded, or misaligned with operational demands. For example, repeated schedule compression may erode supervisory oversight, increase quality shortcuts, weaken environmental controls, and amplify unsafe decision-making. Unlike traditional models focused on failure chains, resilience engineering emphasizes system adaptability, organizational learning, and proactive performance management.

This perspective holds particular relevance for sustainability-driven construction incident analysis because sustainability itself requires adaptive balancing among environmental stewardship, operational performance, worker protection, and long-term system resilience. Performance indicators spanning Environmental, Quality, and Safety domains can therefore be interpreted not merely as compliance metrics but as dynamic indicators of organizational resilience health. Consequently, resilience engineering offers one of the strongest conceptual foundations for integrated sustainability-based root cause analysis in modern construction systems.

➢ *Sustainability in Construction Project Management*

Sustainability has evolved from a peripheral environmental concern into a strategic operational imperative within construction project management. Historically, construction performance assessment was dominated by the traditional project management triangle of cost, time, and quality. While these performance criteria remain essential, contemporary infrastructure delivery increasingly recognizes that project success must also account for environmental stewardship, social responsibility, resource efficiency, occupational safety, governance accountability, and long-term asset resilience [45], [154]. This conceptual transition reflects growing awareness that construction activities exert substantial environmental, economic, and societal impacts across the full project lifecycle, from material extraction and design through construction execution, operation, maintenance, and eventual decommissioning. The sector remains one of the largest global consumers of raw materials, energy, and water, while also contributing significantly to greenhouse gas emissions, waste generation, biodiversity disturbance, and occupational injuries [46]. Consequently, sustainability in construction project management is no longer optional but increasingly foundational to responsible infrastructure governance.

The integration of sustainability into construction management has been accelerated by international climate commitments, stakeholder expectations, regulatory reforms, sustainable finance pressures, and institutional ESG disclosure requirements [47], [156]. Construction organizations are increasingly required to demonstrate measurable accountability not only in environmental protection but also in workforce welfare, ethical governance, lifecycle performance, and operational resilience. These expectations have redefined project delivery from a short-term execution exercise into a broader value creation process requiring multidimensional performance integration. For research focused on sustainability-driven construction incident causation, this broader perspective is particularly relevant because adverse events rarely affect safety alone; they often generate environmental consequences, quality degradation, financial disruption, stakeholder dissatisfaction, and governance failures. Understanding sustainability in construction therefore provides the conceptual basis for integrating Environmental, Quality, and Safety (EQS) performance indicators into incident diagnostic frameworks.

- *Triple Bottom Line Sustainability Framework*

The Triple Bottom Line (TBL) sustainability framework remains one of the most influential conceptual models for understanding sustainability in project management and infrastructure delivery. Originally advanced by Elkington, the framework expands organizational performance evaluation beyond conventional financial outcomes to include environmental, social, and economic dimensions [48]. In construction project management, this model provides a structured basis for assessing sustainability performance through balanced consideration of ecological responsibility, stakeholder welfare, and economic viability.

The environmental dimension focuses on minimizing ecological harm associated with construction activities. This includes reducing greenhouse gas emissions, improving energy efficiency, controlling pollution, managing construction waste, preserving water resources, limiting hazardous material exposure, and protecting ecosystems affected by site development [49], [155]. Construction activities frequently generate significant environmental burdens through diesel-powered equipment operations, raw material extraction, demolition waste, emissions from cement production, and contamination risks arising from poor site controls. Environmental sustainability therefore requires systematic integration of prevention, monitoring, and performance optimization strategies.

The social dimension addresses human-centered impacts of construction operations, including worker health and safety, labor welfare, stakeholder engagement, community disruption, equitable employment practices, and social responsibility in project execution [50], [157]. Construction incidents directly intersect with this dimension because occupational injuries, fatalities, unsafe working conditions, and poor workforce management undermine social sustainability performance. Safety therefore constitutes not merely a compliance obligation but a core sustainability outcome.

The economic dimension encompasses project profitability, lifecycle cost efficiency, asset durability, operational productivity, risk mitigation, and long-term financial resilience [51]. Quality failures, rework, equipment damage, regulatory penalties, litigation costs, and incident-related delays directly erode economic sustainability. Thus, construction incidents represent multidimensional sustainability failures affecting all three TBL pillars simultaneously. This makes the Triple Bottom Line framework particularly relevant to the present study, as it conceptually supports the integration of environmental, quality, and safety variables into unified incident causation analysis.

- *Sustainable Construction Practices*

Sustainable construction practices refer to planning, design, procurement, execution, operation, and management approaches intended to minimize environmental impacts, enhance social well-being, improve resource efficiency, and strengthen lifecycle infrastructure performance [52]. These practices have evolved significantly as construction organizations respond to environmental regulations, green certification frameworks, client sustainability requirements, and investor scrutiny.

Key sustainable construction practices include energy-efficient equipment deployment, sustainable material sourcing, waste minimization strategies, recycling and circular economy initiatives, water conservation, low-emission construction technologies, environmentally responsible demolition methods, and biodiversity-conscious site planning [53]. Green building certification systems such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Envision infrastructure frameworks have further institutionalized sustainability expectations within project delivery.

In operational terms, sustainable construction also involves improved logistics planning, digital monitoring, modular construction approaches, predictive maintenance, environmental auditing, and safer work system design [54]. These practices often intersect directly with incident prevention. For example, improved housekeeping reduces trip hazards and waste accumulation; sustainable equipment maintenance reduces emissions and mechanical failure risks; responsible hazardous material handling reduces both environmental exposure and worker injury potential.

However, implementation challenges remain substantial. Barriers include high initial investment requirements, fragmented supply chains, insufficient technical expertise, weak sustainability governance, contractor resistance, inconsistent regulatory enforcement, and short-term cost prioritization [55], [158]. These implementation constraints often create operational gaps where sustainability intentions fail to translate into practical site-level controls. Such gaps may contribute indirectly to incident occurrence through weakened environmental management, degraded operational discipline, and compromised quality assurance.

- *ESG Relevance in Construction Operations*

Environmental, Social, and Governance (ESG) principles have become increasingly influential in construction operations as institutional investors, regulatory authorities, infrastructure clients, and financial stakeholders demand greater transparency regarding sustainability performance [56], [160]. ESG expands traditional sustainability discourse by emphasizing structured governance accountability alongside environmental and social performance metrics.

The environmental component includes carbon emissions management, energy performance, pollution control, waste minimization, climate adaptation, and responsible resource utilization [57]. Construction firms increasingly face scrutiny regarding emissions from heavy machinery, embodied carbon in building materials, hazardous waste management, and ecological disturbance caused by project activities.

The social component encompasses occupational health and safety, labor rights, workforce welfare, diversity, contractor management, stakeholder engagement, and community impact [58]. Within construction operations, safety performance remains a major ESG indicator because high incident rates may signal weak workforce governance, poor leadership culture, and inadequate operational control systems.

The governance component includes compliance integrity, risk oversight, transparency, ethical procurement, contractor accountability, decision-making quality, and management effectiveness [59], [159]. Governance weaknesses often underlie incident causation through poor communication structures, inadequate supervision, insufficient training investment, weak quality assurance enforcement, and ineffective environmental oversight.

For this study, ESG relevance is particularly important because construction incident causation increasingly reflects governance failures rather than isolated operational deviations. A serious site incident may simultaneously represent environmental non-compliance, social harm, quality breakdown, and governance failure. ESG thinking therefore reinforces the conceptual justification for integrated incident diagnostic models that move beyond traditional safety-only frameworks.

- *Sustainability Maturity in Project Delivery*

Sustainability maturity refers to the degree to which sustainability principles are systematically embedded within organizational strategy, governance systems, operational processes, performance monitoring, and decision-making structures [60]. In construction project delivery, maturity varies significantly across organizations, ranging from basic compliance-oriented approaches to strategically integrated sustainability governance models.

At low maturity levels, sustainability is treated reactively, often limited to regulatory compliance, documentation obligations, or client-driven reporting requirements [61]. Organizations operating at this level may implement isolated environmental controls, safety audits, or quality inspections without systemic integration. Sustainability performance remains fragmented, and incident prevention is typically reactive rather than predictive.

Intermediate maturity levels involve broader sustainability awareness, structured policies, partial digital monitoring, formal reporting systems, and increased stakeholder engagement [62]. However, integration challenges often persist, particularly where environmental, quality, and safety management systems remain organizationally disconnected.

High sustainability maturity is characterized by proactive governance, integrated performance intelligence, predictive analytics, lifecycle decision-making, executive accountability, adaptive risk management, and continuous improvement culture [63]. Organizations at this level treat sustainability not as a compliance function but as a strategic operational capability. Performance indicators are actively monitored for early warning signals, and cross-domain risk relationships are systematically analyzed.

For construction incident prevention, sustainability maturity is particularly consequential. Low-maturity organizations are more likely to rely on fragmented post-incident investigations, whereas mature organizations may adopt integrated predictive risk governance models capable of identifying latent environmental, quality, and safety deterioration before incident occurrence. The present study aligns with this higher maturity paradigm by proposing a sustainability-driven diagnostic framework that leverages performance indicators as proactive root cause intelligence mechanisms.

Sustainability in construction project management provides a critical conceptual foundation for understanding incident causation beyond traditional occupational safety boundaries. The Triple Bottom Line framework establishes multidimensional performance expectations, sustainable construction practices define operational implementation pathways, ESG introduces governance accountability, and sustainability maturity explains organizational readiness for integrated performance management. Collectively, these concepts reinforce the need for construction incident investigation models that recognize environmental, quality, and safety interactions as interconnected sustainability performance determinants rather than isolated compliance domains.

- *Environmental Performance Indicators in Construction*

Environmental performance indicators constitute measurable parameters used to evaluate the environmental effectiveness, ecological compliance, and sustainability outcomes of construction operations. Within modern construction management, these indicators serve as critical decision-support tools for assessing environmental impacts, monitoring compliance performance, identifying operational inefficiencies, and detecting latent environmental risks capable of influencing project safety, quality, and overall sustainability performance [64]. The construction sector remains one of the most environmentally intensive industrial domains globally due to its substantial consumption of raw materials, high energy dependence, waste generation, emissions production, and ecosystem disturbance throughout project lifecycles [65]. Consequently, environmental performance measurement has become a central component of sustainable construction governance.

In the context of construction incident analysis, environmental indicators extend beyond ecological reporting functions and increasingly serve as operational intelligence variables capable of signaling deteriorating site conditions, weak environmental controls, resource mismanagement, and latent hazards. Poor environmental performance may directly contribute to unsafe working conditions, equipment degradation, regulatory violations, productivity disruptions, and quality failures. For example, inadequate waste segregation may create trip hazards, uncontrolled dust emissions may impair worker visibility and respiratory safety, poor hazardous substance management may increase exposure risks, and inefficient water control may destabilize site conditions [66]. Accordingly, environmental performance indicators provide important analytical value for sustainability-driven root cause analysis.

- *Waste Generation Rates*

Waste generation rate is one of the most widely used environmental performance indicators in construction sustainability assessment. It measures the quantity of waste generated relative to project activity, commonly expressed in terms of kilograms per square meter of constructed area, tonnes per project phase, or waste volume relative to material input [67]. Construction and demolition waste remains a major global environmental challenge due to the sector's dependence on bulk materials such as concrete, steel, timber, asphalt, packaging materials, excavation spoil, and finishing products.

Excessive waste generation often reflects inefficient planning, poor procurement management, inaccurate material estimation, defective execution, rework, weak inventory control, and inadequate on-site handling practices [68]. These inefficiencies are not solely environmental concerns; they frequently reveal broader operational deficiencies that may contribute to construction incidents. Accumulated debris obstructs access routes, increases trip-and-fall exposure, interferes with emergency movement, creates fire load accumulation, and may conceal unsafe site conditions. Improper waste storage may also compromise equipment movement and increase collision risk.

From a sustainability-driven root cause perspective, waste generation serves as a diagnostic indicator of organizational discipline, operational efficiency, and site control effectiveness. Persistent abnormal waste generation may indicate latent management failures relevant to incident causation.

- *Dust Emissions*

Dust emission levels are critical environmental performance indicators in construction due to their substantial occupational health, environmental, and operational implications. Construction dust originates from excavation, demolition, concrete cutting, grinding, earth movement, material handling, aggregate transport, and vehicular movement across unpaved surfaces [69]. Particulate matter emissions, particularly respirable fractions such as PM_{10} and $PM_{2.5}$, are of particular concern because of their ability to penetrate respiratory systems and degrade air quality.

Beyond long-term health consequences such as silicosis, respiratory irritation, chronic obstructive pulmonary disease, and cardiovascular stress, dust emissions also create immediate operational risks [70]. Reduced visibility may impair equipment operation, elevated particulate loading may compromise machinery performance, dust deposition may interfere with electrical systems, and airborne contaminants may reduce workforce concentration or task accuracy.

Dust emissions also interact with safety and quality domains. For instance, excessive dust may obscure warning signage, interfere with surface preparation quality, contaminate installed materials, and increase respiratory distress among workers performing physically demanding tasks. Consequently, dust emissions are not merely environmental compliance metrics but operational indicators of latent construction instability.

Environmental monitoring of dust typically involves particulate concentration measurements, air quality threshold exceedance frequency, dust suppression effectiveness, and complaint incidence tracking [71]. Within sustainability-driven incident analysis, repeated dust control failures may indicate inadequate environmental governance, weak supervision, or poor operational planning.

- *Noise Pollution Levels*

Noise pollution is another important environmental performance indicator within construction operations, particularly in urban infrastructure projects, industrial construction, demolition activities, and heavy equipment deployment environments. Construction noise originates from pile driving, excavation machinery, generators, compressors, cutting equipment, transport vehicles, and mechanical operations [72].

Noise monitoring commonly uses sound pressure measurements expressed in decibels (dB), exposure duration tracking, exceedance frequency relative to regulatory thresholds, and occupational exposure assessments [73]. While noise is traditionally treated as an environmental nuisance affecting surrounding communities, its implications for construction safety and operational performance are equally significant.

Elevated noise levels may interfere with communication among workers, impair verbal warning transmission, reduce situational awareness, increase fatigue, and contribute to human error in complex tasks [74]. Prolonged exposure may also degrade concentration, increase stress, and impair decision-making quality. In high-risk construction environments involving crane coordination, confined space operations, lifting activities, or mobile equipment interactions, communication breakdowns caused by excessive noise may directly contribute to incident occurrence.

Thus, persistent noise exceedance should be interpreted not only as environmental non-compliance but also as an operational hazard indicator relevant to incident causation analysis.

- *Hazardous Material Handling Compliance*

Hazardous material handling compliance measures the degree to which construction activities conform to established procedures for storage, transport, labeling, use, containment, and disposal of hazardous substances [75]. Construction projects frequently involve hazardous materials including fuels, lubricants, solvents, coatings, adhesives, concrete additives, asbestos-containing materials, welding gases, chemical cleaners, and contaminated demolition waste.

Compliance indicators may include spill occurrence frequency, hazardous storage inspection outcomes, labeling conformity rates, containment adequacy, incident reporting frequency, safety data sheet accessibility, and regulatory audit performance [76]. Poor hazardous material management presents direct environmental risks including soil contamination, stormwater pollution, air emissions, and chemical release events. Simultaneously, it presents acute occupational hazards such as burns, toxic exposure, inhalation injury, fire escalation, and explosion risks.

From a root cause analysis perspective, hazardous material compliance failures often reveal broader governance deficiencies including weak training systems, poor supervision, inadequate procedural enforcement, deficient procurement oversight, and ineffective environmental risk management. Repeated hazardous material non-compliance therefore represents a significant latent performance indicator for incident causation.

- *Resource Consumption Indicators*

Resource consumption indicators assess the efficiency with which construction projects utilize raw materials, fuel, consumables, and natural resources throughout project execution [77]. Common metrics include material consumption intensity, fuel usage rates, equipment utilization efficiency, procurement waste ratios, and embodied resource consumption relative to project output.

Construction remains highly resource-intensive due to dependence on cement, steel, aggregates, timber, fuel-powered machinery, packaging materials, and temporary infrastructure systems [65]. Abnormal resource consumption often reflects operational inefficiencies such as poor planning, excessive rework, defective material handling, inefficient logistics coordination, and weak equipment management.

These inefficiencies may indirectly contribute to incident causation. Excessive fuel dependency may increase hazardous storage exposure; poor material consumption control may generate cluttered workspaces; inefficient logistics may increase traffic conflicts; and overconsumption patterns may indicate weak operational discipline or deficient planning systems [78].

Thus, resource consumption indicators serve as broader organizational health metrics with diagnostic relevance extending beyond environmental reporting.

- *Energy Efficiency Metrics*

Energy efficiency metrics measure the effectiveness with which construction operations convert energy inputs into productive project outputs while minimizing waste and environmental burden [79]. Indicators may include fuel consumption per equipment operating hour, energy intensity per unit of project output, equipment idle-time ratios, generator efficiency performance, and carbon intensity proxies.

Construction energy demand is driven by heavy machinery, transport operations, lighting systems, temporary facilities, pumping systems, material handling equipment, and site services [65]. Inefficient energy performance often reflects poor equipment maintenance, suboptimal scheduling, aging machinery, excessive idling, weak supervisory oversight, and operational coordination failures.

These deficiencies may contribute to incident risks through equipment overheating, mechanical failure, unplanned operational disruptions, hazardous emissions accumulation, and reduced operational reliability [80]. Energy inefficiency may therefore serve as an indirect diagnostic signal of deteriorating technical and managerial performance.

Within sustainability-driven incident analysis, energy metrics provide useful operational intelligence for identifying systemic inefficiencies with latent safety implications.

- *Water Management Indicators*

Water management indicators assess how effectively construction operations control water use, runoff, contamination risk, and site drainage performance [81]. Common indicators include water consumption intensity, stormwater control effectiveness, runoff contamination frequency, leakage incidents, wastewater management performance, and drainage system adequacy.

Construction water use is associated with dust suppression, concrete mixing, curing operations, equipment cleaning, sanitary systems, hydro-demolition, and site maintenance [82]. Poor water management may create both environmental and operational hazards. Uncontrolled runoff may transport sediments, oils, chemicals, and pollutants into receiving environments. Poor drainage may generate slip hazards, destabilize excavation zones, weaken temporary structures, and compromise access routes.

Regulatory frameworks such as construction stormwater management requirements emphasize pollution prevention planning due to the substantial environmental risk associated with uncontrolled site runoff [83]. From a safety perspective, repeated water management failures may indicate weak environmental supervision, inadequate site planning, poor drainage design, or deficient operational coordination.

As a root cause indicator, water management performance provides important evidence of latent environmental control weaknesses that may interact directly with construction incident formation.

Overall, environmental performance indicators provide far more than ecological reporting value within construction management. Waste generation, dust emissions, noise exposure, hazardous material compliance, resource consumption, energy efficiency, and water management collectively provide measurable intelligence regarding operational discipline, environmental governance, latent hazard accumulation, and systemic management performance. For sustainability-driven construction incident analysis, these indicators offer critical diagnostic inputs capable of strengthening root cause identification beyond conventional safety-only investigation models.

Fig 2 Water Management Performance as a Root Cause Indicator in Construction Incidence Analysis

- ➢ *Quality Performance Indicators in Construction*

Quality performance indicators are measurable parameters used to assess the effectiveness, consistency, and reliability of construction processes, materials, workmanship, equipment performance, and compliance with specified project requirements. Within construction project management, quality performance has traditionally been associated with conformance to design specifications, adherence to engineering standards, durability expectations, and customer satisfaction outcomes [84]. However, in contemporary construction systems, quality performance extends beyond product conformity to encompass operational discipline, process integrity, defect prevention capability, maintenance effectiveness, and organizational control maturity. This broader interpretation is particularly relevant in construction incident analysis because many adverse events emerge not solely from explicit safety failures but from latent quality breakdowns embedded within technical execution processes.

The relationship between construction quality and incident causation is well established in engineering risk literature. Defective workmanship, incomplete inspections, material non-conformance, equipment degradation, procedural deviations, and rework-intensive operations frequently contribute to structural instability, mechanical failures, unsafe working conditions, and operational disruptions [85]. Poor quality performance often indicates underlying governance weaknesses including deficient supervision, inadequate competency management, weak procurement controls, poor maintenance planning, and ineffective quality assurance implementation. Consequently, quality performance indicators provide critical diagnostic intelligence for sustainability-driven root cause analysis by revealing latent operational deficiencies that may precipitate construction incidents.

- *Rework Frequency*

Rework frequency is one of the most significant quality performance indicators in construction management because it reflects the extent to which completed work must be repeated, corrected, modified, or replaced due to errors, defects, omissions, non-compliance, or technical inadequacies [86]. Rework is commonly measured as the frequency of corrective interventions, percentage of project cost attributable to rework, number of repeated tasks, or time lost due to reconstruction activities.

Construction rework arises from numerous sources including design errors, poor workmanship, inaccurate interpretation of specifications, material incompatibility, inadequate supervision, ineffective communication, and insufficient quality control [87]. While traditionally regarded as a cost and productivity issue, rework also carries substantial safety and environmental implications. Repetitive demolition, dismantling, material replacement, and corrective execution increase worker exposure to hazardous operations, prolong site occupancy, increase equipment interaction frequency, generate waste, and elevate energy consumption.

From an incident causation perspective, persistent rework may indicate latent systemic weaknesses rather than isolated execution mistakes. High rework frequency often reflects weak process discipline, poor design coordination, inadequate competency assurance, or ineffective inspection regimes. Such conditions create operational instability capable of increasing accident susceptibility. Therefore, rework frequency serves not merely as a quality metric but as an important predictor of broader organizational failure conditions.

- *Defect Occurrence Rates*

Defect occurrence rate measures the frequency with which construction outputs fail to meet specified technical, engineering, or performance requirements [88]. Defects may involve dimensional inaccuracies, structural inconsistencies, improper installation, surface failures, mechanical malfunctions, electrical faults, incomplete assemblies, or performance deficiencies identified during execution, testing, or commissioning.

Defect rates are commonly expressed as defects per project phase, defects per inspection unit, defect density relative to work volume, or defect recurrence trends over time. High defect occurrence suggests weaknesses in workmanship quality, supervisory effectiveness, technical competence, procedural compliance, design clarity, or supplier reliability [89].

In construction environments, defects may directly create hazardous conditions. Structural defects can compromise load-bearing integrity, electrical defects may create electrocution or fire risks, mechanical defects may trigger equipment failures, and installation errors may create collapse or operational hazards. Even where defects do not immediately result in accidents, they often indicate deteriorating technical control conditions that elevate incident exposure.

Within sustainability-driven root cause analysis, defect occurrence functions as a leading quality indicator capable of revealing latent technical risk accumulation before severe incidents occur. Persistent defect trends may therefore serve as early warning signals of declining operational resilience.

- *Inspection Non-Conformance Rates*

Inspection non-conformance rate measures the frequency at which construction activities, materials, equipment, or completed work fail formal inspection criteria relative to applicable specifications, quality standards, regulatory requirements, or contractual obligations [90]. This indicator reflects the effectiveness of quality assurance systems and the degree of operational compliance with predefined technical expectations.

Inspection failures may involve dimensional deviations, improper material installation, incomplete procedural compliance, welding defects, electrical non-conformities, structural misalignment, inadequate documentation, or failure to meet environmental or safety-related engineering specifications. Non-conformance frequency is typically tracked through inspection reports, punch lists, quality audits, and commissioning assessments.

High inspection non-conformance rates indicate breakdowns in process control, supervision, technical competency, or work planning [91]. From a construction incident perspective, these deficiencies are particularly significant because failed inspections often expose latent hazards before adverse events materialize. For example, failure to detect scaffold deficiencies, lifting gear defects, temporary works instability, or electrical non-compliance may directly increase incident risk.

Repeated inspection failures also indicate organizational weaknesses in quality governance and control enforcement. Accordingly, inspection non-conformance rates provide valuable diagnostic insight for root cause analysis by revealing measurable operational discipline deficiencies.

- *Material Rejection Rates*

Material rejection rate is a quality performance indicator measuring the proportion of procured or delivered construction materials that fail acceptance criteria due to non-conformance with technical specifications, quality standards, dimensional tolerances, performance requirements, or regulatory compliance expectations [92]. Rejected materials may include defective steel, compromised concrete batches, damaged mechanical components, contaminated aggregates, non-compliant electrical equipment, or unsuitable finishing products.

Material rejection is commonly caused by supplier quality failures, transportation damage, poor storage conditions, specification mismatches, inadequate procurement verification, or substandard manufacturing processes [93]. High rejection rates often indicate weaknesses in procurement governance, supplier management, incoming inspection systems, logistics control, or quality assurance enforcement.

The relevance of this indicator to construction incident analysis is substantial. Defective materials that escape detection may compromise structural performance, equipment reliability, fire safety, or operational integrity. Even properly rejected materials may indicate upstream control failures capable of affecting broader project risk performance.

From a sustainability perspective, high material rejection also contributes to waste generation, additional transport emissions, cost escalation, schedule disruption, and resource inefficiency. Thus, material rejection rate provides multidimensional diagnostic value linking quality performance with environmental and safety implications.

- *Process Deviation Frequency*

Process deviation frequency measures the occurrence of departures from approved construction procedures, technical workflows, engineering methods, or operational control protocols [94]. Deviations may involve unauthorized changes in task sequencing, incomplete execution steps, bypassed approvals, undocumented procedural modifications, improper installation methods, or non-adherence to standard operating instructions.

Construction processes depend heavily on procedural consistency to ensure technical quality, safety reliability, and operational predictability. Frequent deviations suggest weak supervision, inadequate competency, production pressure, poor documentation control, ineffective communication, or deficient management oversight [95].

Process deviations are particularly important in incident causation because they often create hidden risk conditions before incidents occur. Unauthorized lifting modifications, altered excavation procedures, improper concrete curing methods, bypassed isolation protocols, or deviations in temporary works installation may compromise structural stability, equipment safety, or worker protection.

Within sustainability-driven diagnostic frameworks, process deviation frequency serves as an indicator of operational governance maturity and control discipline. Repeated deviations frequently reflect systemic organizational weaknesses rather than isolated individual actions, making this a critical root cause analysis variable.

- *Equipment Reliability and Maintenance Quality*

Equipment reliability and maintenance quality represent essential quality performance indicators within construction environments due to the sector's extensive dependence on machinery, mechanical systems, lifting equipment, transport assets, power tools, temporary infrastructure systems, and construction technology platforms [96]. Equipment reliability refers to the probability that machinery performs intended functions without failure under specified operational conditions, while maintenance quality reflects the effectiveness of inspection, servicing, repair, preventive maintenance, and technical performance assurance activities.

Common metrics include mean time between failures, breakdown frequency, maintenance compliance rates, inspection completion ratios, downtime duration, and corrective maintenance recurrence [97]. Poor equipment reliability often reflects inadequate preventive maintenance, weak inspection discipline, poor operator competency, defective spare parts management, excessive equipment aging, or improper utilization practices.

The implications for construction incident causation are substantial. Equipment failures frequently contribute to lifting accidents, mechanical collapse, struck-by incidents, power failures, fire events, hydraulic failures, and uncontrolled machinery movement [98]. Maintenance deficiencies may also increase emissions, energy inefficiency, hazardous leaks, and operational disruption.

From a sustainability perspective, equipment reliability intersects directly with environmental performance, quality assurance, operational productivity, and worker safety. Persistent maintenance failures often reveal broader systemic governance weaknesses, making this indicator particularly valuable in integrated root cause analysis.

Overall, quality performance indicators provide a critical analytical foundation for understanding latent technical and operational contributors to construction incidents. Rework frequency, defect occurrence, inspection non-conformance, material rejection, process deviation, and equipment reliability collectively reflect organizational control effectiveness, technical discipline, and operational resilience. Within sustainability-driven construction incident analysis, these indicators offer measurable evidence of latent quality deterioration capable of interacting with environmental and safety failures to produce adverse events. Their integration into root cause analytical frameworks therefore enhances diagnostic depth beyond conventional safety-centric investigation approaches.

➢ *Safety Performance Indicators in Construction*

Safety performance indicators are measurable parameters used to evaluate the effectiveness of occupational health and safety management systems, hazard control mechanisms, workforce behavioral compliance, and incident prevention capability within construction environments. In construction project management, safety indicators serve as critical decision-support tools for monitoring operational risk exposure, identifying deteriorating control conditions, assessing management performance, and informing preventive interventions [12]. Given the inherently hazardous nature of construction operations, characterized by work at height, heavy equipment interaction, excavation activities, temporary structures, electrical exposure, confined space operations, material handling, and dynamic workforce interfaces, safety performance measurement remains indispensable for effective risk governance [2].

Traditionally, construction safety performance assessment relied heavily on lagging indicators such as accident frequency, fatality rates, compensation claims, and injury severity metrics [99]. While these measures provide valuable retrospective insights into adverse outcomes, they are limited by their inability to provide early warning signals before incidents occur. Contemporary construction safety management increasingly emphasizes a combination of lagging and leading indicators, recognizing that proactive performance metrics offer greater predictive value for incident prevention [32]. Leading indicators provide measurable evidence of operational deterioration before incident manifestation, while lagging indicators quantify realized safety outcomes after failures have occurred.

Within the context of sustainability-driven construction incident analysis, safety performance indicators provide essential operational intelligence that complements environmental and quality metrics. Poor safety indicator performance may reveal latent governance deficiencies, weak behavioral control, ineffective supervision, procedural non-compliance, inadequate workforce engagement, and declining organizational resilience. Because safety failures frequently interact with environmental and quality deficiencies, their inclusion within an integrated root cause analysis framework is conceptually and operationally essential.

- *Lost Time Injury Frequency Rate*

Lost Time Injury Frequency Rate (LTIFR) is one of the most widely used lagging safety performance indicators in construction safety management. LTIFR measures the number of work-related injuries resulting in lost productive work time relative to total hours worked, typically standardized per one million or two hundred thousand labor hours [100]. This indicator provides a quantitative measure of the frequency of serious incidents affecting workforce operational continuity.

LTIFR remains a central benchmark for organizational safety performance because it captures incidents with measurable operational consequences including productivity disruption, compensation exposure, workforce absence, and project schedule impacts. Elevated LTIFR values may indicate ineffective hazard identification, weak control implementation, poor training quality, inadequate supervision, or systemic operational deficiencies [101].

However, LTIFR possesses notable limitations. As a lagging indicator, it reflects incidents that have already occurred rather than providing predictive insight into emerging risks. It may also underrepresent serious latent safety deterioration where incidents narrowly avoided injury outcomes. Nonetheless, within integrated root cause analysis, LTIFR remains useful for correlating incident severity patterns with broader environmental, quality, and organizational performance conditions.

- *Near Miss Reporting Frequency*

Near miss reporting frequency is a leading safety performance indicator measuring the rate at which potentially hazardous events are identified and formally reported before resulting in injury, damage, or operational loss [102], [161]. Near misses represent incidents in which adverse consequences were narrowly avoided due to chance, intervention, timing, or limited exposure.

In construction environments, examples include dropped objects that miss personnel, scaffold instability detected before collapse, electrical exposure avoided through timely intervention, vehicle-pedestrian conflict events, or unplanned equipment movements without injury outcomes. Near miss frequency serves as a valuable indicator because it reveals hazard presence without requiring injury occurrence.

High near miss reporting rates may indicate strong reporting culture, workforce engagement, hazard awareness, and proactive safety maturity [103], [162]. Conversely, unusually low reporting frequency may not necessarily indicate safe conditions; it may instead reflect underreporting, weak safety culture, fear of blame, inadequate communication systems, or management disengagement.

From a root cause perspective, near miss patterns provide early evidence of deteriorating operational control conditions. Repeated near miss trends in particular work categories may reveal systemic weaknesses requiring intervention before major incidents occur. Accordingly, near miss reporting frequency is one of the most diagnostically valuable leading indicators in construction safety analytics.

- *Unsafe Act Occurrence*

Unsafe act occurrence measures the frequency of observed worker behaviors that deviate from established safety procedures, operational controls, or accepted safe work practices [35]. Common unsafe acts in construction include failure to use fall protection, bypassing lockout procedures, improper lifting practices, unauthorized equipment operation, neglect of confined space protocols, unsafe material handling, and failure to follow permit requirements.

Behavioral safety models historically emphasized unsafe acts as primary causal contributors to workplace incidents [34], [163]. Indeed, unsafe acts may directly precipitate accidents where immediate procedural violations create exposure to hazards. Frequent unsafe act observations may indicate inadequate training, poor supervision, weak behavioral accountability, production pressure, fatigue, insufficient hazard awareness, or deficient leadership culture [104].

However, contemporary safety science cautions against simplistic attribution of incidents solely to worker behavior [37], [164]. Unsafe acts frequently emerge from deeper organizational conditions such as unrealistic schedules, poor work design, inadequate tools, conflicting procedures, or supervisory failures. Therefore, while unsafe act occurrence remains an important safety indicator, its analytical interpretation should be systemic rather than blame-centered.

- *Unsafe Condition Prevalence*

Unsafe condition prevalence measures the occurrence of hazardous physical, environmental, equipment-related, or operational site conditions capable of increasing accident risk [12]. Examples include defective scaffolding, exposed wiring, poor housekeeping, unstable excavations, blocked access routes, inadequate lighting, faulty lifting gear, damaged PPE, uncontrolled chemical exposure, and unsafe equipment positioning.

Unlike unsafe acts, which reflect behavioral deviations, unsafe conditions represent environmental or technical failures embedded within the work environment. High unsafe condition prevalence often indicates poor inspection discipline, weak maintenance systems, inadequate supervision, deficient hazard identification, or ineffective corrective action implementation [105].

Unsafe conditions are particularly relevant in construction because dynamic project environments evolve rapidly, creating frequent changes in exposure conditions. A site deemed safe in the morning may become hazardous later due to weather, equipment movement, excavation progress, material accumulation, or temporary works changes.

Within sustainability-driven incident analysis, unsafe condition prevalence also overlaps with environmental and quality indicators. Poor housekeeping may reflect waste management deficiencies, defective temporary works may indicate quality failures, and hazardous site layout conditions may reveal governance weaknesses. Thus, unsafe condition prevalence serves as a highly integrative safety performance metric.

- *Permit-to-Work Compliance*

Permit-to-work (PTW) compliance measures adherence to formal authorization procedures governing high-risk construction activities such as hot work, confined space entry, excavation, electrical isolation, lifting operations, and hazardous maintenance interventions [106]. Permit systems function as structured administrative controls intended to ensure hazard identification, authorization review, control verification, and communication prior to task execution.

PTW compliance indicators may include permit issuance accuracy, authorization completeness, expired permit occurrence, procedural adherence rates, permit audit findings, and deviation frequency. High compliance suggests mature procedural governance, disciplined operational control, and effective supervisory oversight [107].

Poor permit compliance may indicate production pressure, inadequate training, weak safety culture, insufficient supervision, or administrative breakdown. Such failures are especially critical because permit-governed tasks typically involve elevated hazard exposure. Numerous severe construction incidents involving fires, electrocutions, excavation collapses, and confined space fatalities have been linked to permit failures.

As a leading indicator, PTW compliance provides strong predictive insight into organizational safety discipline and operational control effectiveness.

- *Toolbox Talk Participation*

Toolbox talk participation is a leading safety indicator measuring workforce engagement in short, structured pre-task safety briefings conducted to communicate hazards, reinforce procedures, discuss task-specific risks, and strengthen situational awareness [108]. These briefings are widely used in construction due to the sector's dynamic risk profile and changing daily work conditions.

Participation metrics may include attendance rates, frequency of conducted sessions, relevance of discussion topics, workforce engagement levels, and documented completion consistency. Effective toolbox talks improve communication, hazard awareness, behavioral reinforcement, and workforce preparedness [109].

Low participation or poor-quality toolbox sessions may indicate communication weaknesses, poor supervisory engagement, inadequate safety leadership, or workforce disengagement. However, attendance alone does not necessarily guarantee effectiveness; poorly structured or perfunctory sessions may offer limited practical benefit.

Within incident analysis, toolbox talk participation serves as an indicator of organizational safety culture maturity and preventive communication effectiveness. Persistent deficiencies may reveal latent governance weaknesses relevant to root cause formation.

- *PPE Compliance Metrics*

Personal Protective Equipment (PPE) compliance metrics measure the extent to which workers correctly use required protective equipment appropriate to specific construction hazards [110]. Common PPE includes helmets, safety boots, gloves, respiratory protection, eye protection, hearing protection, fall arrest systems, high-visibility clothing, and task-specific specialized equipment.

Compliance indicators may include observation-based adherence rates, violation frequency, adequacy of equipment availability, equipment suitability, replacement timeliness, and disciplinary non-compliance records. High PPE compliance reflects workforce awareness, supervisory enforcement, adequate provisioning, and strong procedural discipline [111].

However, PPE represents the lowest tier within the hierarchy of hazard controls and should not substitute for engineering or administrative protections [12], [165],[170]. High PPE compliance does not necessarily indicate comprehensive safety maturity if upstream hazards remain poorly controlled.

From a diagnostic perspective, repeated PPE non-compliance may reveal weak training systems, poor supervision, insufficient equipment provision, discomfort-related resistance, or cultural normalization of unsafe practices. As such, PPE metrics remain useful leading indicators within integrated safety performance assessment.

Overall, safety performance indicators provide essential operational intelligence for understanding construction incident causation. Lost time injury frequency offers retrospective severity measurement, while near miss reporting, unsafe act occurrence, unsafe condition prevalence, permit compliance, toolbox participation, and PPE adherence provide increasingly proactive insight into latent safety performance conditions. Within sustainability-driven root cause analysis, these indicators contribute critical evidence regarding workforce behavior, operational discipline, management control effectiveness, and organizational resilience. Their integration with environmental and quality performance indicators strengthens the development of a multidimensional incident diagnostic framework capable of addressing the complexity of modern construction systems.

➢ *Root Cause Analysis Models in Incident Investigation*

Root Cause Analysis (RCA) constitutes a systematic investigative approach used to identify the underlying causal mechanisms responsible for adverse events, operational failures, or incident occurrence rather than merely documenting immediate symptoms or observable consequences [31]. In construction project environments, root cause analysis plays a critical role in incident prevention because construction failures rarely emerge from isolated technical defects or frontline behavioral deviations. Instead, incidents often arise through interacting human, technical, organizational, procedural, environmental, and managerial failures embedded within complex project delivery systems [38]. Consequently, effective incident investigation requires analytical tools capable of moving beyond surface-level observations toward structured identification of latent causal pathways.

The evolution of root cause analysis methodologies reflects broader developments in safety science, engineering risk management, systems thinking, and organizational reliability research. Early RCA models emphasized direct causality and linear fault progression, while contemporary frameworks increasingly recognize organizational complexity, multi-causal interactions, defense failures, human-system integration, and adaptive risk behavior [40]. Within construction management, root cause analysis tools are used to investigate occupational injuries, structural failures, equipment accidents, fire incidents, environmental releases, quality breakdowns, and high-potential near misses. However, the effectiveness of any RCA methodology depends heavily on its analytical assumptions, causal depth, contextual suitability, and ability to accommodate multidimensional performance interactions.

For sustainability-driven construction incident analysis, evaluating conventional root cause analysis models is essential because many existing tools were developed primarily for safety event investigation and may inadequately integrate environmental and quality performance dimensions. The following conceptual review examines major root cause analysis models commonly used in incident investigation.

- *Whys Analysis*

The 5 Whys method is one of the simplest and most widely adopted root cause investigation techniques, originally developed within industrial quality management systems as part of Toyota's production improvement methodology [112]. The method involves repeatedly asking the question "why" following an incident until the underlying causal mechanism is identified, typically through approximately five iterative inquiry stages, although the exact number may vary depending on case complexity.

For example, if a worker suffers an injury from scaffold collapse, the inquiry may progress through sequential questions regarding why the collapse occurred, why the support failed, why inspection deficiencies existed, why maintenance was neglected, and why supervisory controls failed. This structured questioning process encourages investigators to move beyond immediate symptoms toward deeper causative explanations.

The principal strengths of the 5 Whys method include simplicity, low implementation cost, rapid deployment, accessibility to multidisciplinary teams, and intuitive usability [113]. It is particularly effective for straightforward operational failures where causal pathways are relatively linear and clearly observable.

However, the method has important limitations in complex construction environments. It relies heavily on investigator judgment, may prematurely terminate inquiry, and often assumes singular linear causality despite the multi-causal nature of construction incidents [114]. In projects characterized by contractor interfaces, environmental variability, procedural complexity, and organizational uncertainty, the 5 Whys may oversimplify interacting failure mechanisms. Consequently, while useful as a preliminary investigative tool, its standalone adequacy for sustainability-driven root cause diagnostics is limited.

- *Fishbone (Ishikawa) Analysis*

Fishbone analysis, also known as Ishikawa cause-and-effect analysis, is a structured RCA tool designed to systematically categorize potential causes contributing to a defined adverse event [115]. The model visually represents causal branches extending from a central problem statement, often organized into categories such as methods, manpower, machinery, materials, measurement, and environment.

In construction incident investigation, Fishbone analysis is useful for identifying diverse contributing factors such as equipment malfunction, procedural failures, supervision deficiencies, material defects, environmental hazards, communication breakdowns, and human performance issues. Its visual structure encourages broad causal exploration and multidisciplinary participation.

A major advantage of Fishbone analysis is its ability to promote structured brainstorming and prevent overly narrow focus on obvious causes [116]. It supports comprehensive identification of contributing factors and can accommodate environmental, quality, and safety variables simultaneously.

Nevertheless, Fishbone analysis remains largely qualitative and does not inherently prioritize causal significance or model dynamic interactions between contributing factors [117]. It identifies possible causes but offers limited analytical depth for validating causal dependencies or quantifying risk relationships. In highly complex construction failures, this may reduce diagnostic precision.

- *Fault Tree Analysis*

Fault Tree Analysis (FTA) is a deductive, logic-based RCA methodology used to analyze the pathways through which combinations of failures lead to a defined undesired event [118]. Developed for engineering reliability and safety-critical systems analysis, FTA uses Boolean logic structures to represent failure relationships through "AND" and "OR" gate constructs.

In construction applications, FTA may be used to investigate structural collapse, equipment failure, fire events, lifting incidents, or electrical failures by mapping combinations of technical, human, and procedural breakdowns that collectively produce incident outcomes [119].

FTA offers several strengths including rigorous logical structure, analytical transparency, reproducibility, and capacity for quantitative reliability modeling where probability data are available. It is particularly effective for technically structured failure analysis involving well-defined systems.

However, FTA exhibits limitations in dynamic construction environments. The method assumes relatively stable causal structures, depends on clearly definable failure logic, and may inadequately capture adaptive human behavior, evolving site conditions, organizational complexity, and feedback-driven interactions [120]. Additionally, data demands may constrain practical application in less formally instrumented construction settings.

- *Event Tree Analysis*

Event Tree Analysis (ETA) is an inductive analytical method used to examine the possible consequence pathways that may unfold following an initiating event [121]. Unlike FTA, which reasons backward from failure outcome to causal contributors, ETA reasons forward from an initiating condition to evaluate how system responses influence subsequent outcomes.

In construction incident analysis, ETA may be used to assess scenarios such as fire escalation following equipment ignition, collapse propagation after temporary works failure, or hazardous release consequences following containment breach. The method evaluates branching outcomes depending on the success or failure of safety barriers, emergency responses, or control interventions.

ETA is valuable for consequence modeling, emergency planning, barrier evaluation, and scenario-based risk analysis [122]. It supports visualization of escalation pathways and helps identify weaknesses in mitigation systems.

However, ETA is less effective for identifying deep organizational root causes because its primary focus lies in consequence progression rather than causal origin analysis. Its applicability to sustainability-driven diagnostic investigation is therefore more complementary than primary.

- *Bow-Tie Analysis*

Bow-Tie analysis combines features of Fault Tree Analysis and Event Tree Analysis within a unified risk visualization framework [123]. The method places a central hazardous event at the center of the diagram, with causal pathways leading toward the event on the left side and consequence pathways extending from the event on the right side. Preventive barriers are mapped before the event, while mitigation barriers are mapped afterward.

In construction contexts, Bow-Tie analysis is widely used for high-risk operations including lifting activities, confined space entry, excavation work, hazardous chemical handling, and fire prevention planning [124]. The method provides a highly intuitive visual representation of threat sources, barrier effectiveness, escalation mechanisms, and consequence control structures.

Its strengths include strong communication value, practical usability, integration of preventive and mitigative thinking, and suitability for multidisciplinary risk reviews. The framework also aligns conceptually with sustainability governance because barriers may include environmental, quality, and safety controls.

However, Bow-Tie analysis remains partly static and does not inherently model evolving adaptive interactions, latent organizational failures, or probabilistic complexity [125]. It is particularly effective for barrier management but less robust as a deep systemic root cause diagnostic tool.

- *Human Factors Analysis and Classification System (HFACS)*

The Human Factors Analysis and Classification System (HFACS) was developed as a structured framework for analyzing human and organizational contributors to incidents, originally within aviation safety [126]. HFACS extends beyond frontline operator behavior by categorizing failures across multiple hierarchical levels including unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences.

Within construction incident investigation, HFACS provides a more sophisticated alternative to simplistic behavioral blame models by recognizing supervisory failures, environmental stressors, organizational culture, communication weaknesses, resource constraints, and management-level influences [127].

The framework's principal strength lies in its structured human-systems perspective and ability to move incident investigation beyond worker-centric attribution. It offers analytical depth regarding latent organizational contributors and is adaptable across multiple industrial domains.

However, HFACS retains strong emphasis on human performance and organizational behavior, with comparatively weaker direct treatment of environmental sustainability metrics, technical quality failures, and infrastructure performance interactions [128]. For integrated sustainability-driven incident diagnostics, HFACS offers valuable conceptual depth but incomplete multidimensional coverage.

- *Tripod Beta*

Tripod Beta is a root cause investigation methodology developed for high-risk industrial sectors to identify both active failures and latent organizational weaknesses contributing to incidents [129]. The framework emphasizes the interaction between hazardous events, failed barriers, and underlying organizational conditions termed General Failure Types (GFTs), including communication failures, design weaknesses, training deficiencies, maintenance shortcomings, procedural inadequacies, and organizational culture issues.

Tripod Beta is particularly useful for identifying systemic management failures rather than focusing solely on frontline operational deviations. In construction environments, it can support investigation of major accidents involving equipment failures, procedural breakdowns, contractor coordination failures, and barrier management weaknesses [130].

The model's strengths include structured systemic thinking, barrier-focused analysis, latent organizational diagnosis, and emphasis on management-level accountability. These features align well with sustainability-oriented risk governance principles.

However, implementation complexity, investigator training requirements, and dependence on high-quality causal evidence may limit routine deployment in some construction settings. Furthermore, while conceptually broad, explicit environmental and quality sustainability dimensions are not always directly operationalized.

- *TapRooT*

TapRooT is a commercially structured root cause investigation methodology designed to identify both immediate and systemic contributors to incidents through guided analytical questioning, causal tree logic, and evidence-based categorization [131]. The method emphasizes systematic evidence gathering, structured causal progression, and correction strategy development.

In construction applications, TapRooT is used for injury investigations, equipment failures, process incidents, operational disruptions, and safety event analysis. Its structured logic reduces investigator subjectivity compared with informal qualitative methods and supports consistent documentation [132].

TapRooT's strengths include procedural discipline, broad applicability, evidence orientation, and corrective action integration. The methodology encourages investigators to examine management systems, human performance, procedures, training, equipment, and environmental conditions.

Nevertheless, its proprietary nature, implementation cost, training dependency, and procedural rigidity may limit widespread academic and operational adoption. Additionally, like many established RCA tools, its traditional application remains predominantly safety-centric rather than explicitly sustainability-integrated.

Overall, root cause analysis methodologies vary substantially in conceptual assumptions, analytical depth, operational complexity, and suitability for construction incident investigation. Simpler tools such as 5 Whys and Fishbone analysis offer accessibility but limited systemic sophistication. Engineering models such as FTA, ETA, and Bow-Tie provide structured failure logic but may struggle with dynamic organizational complexity. HFACS, Tripod Beta, and TapRooT offer deeper systemic investigation capability but remain partially constrained by domain emphasis or implementation complexity. Importantly, most conventional RCA frameworks were not originally developed to integrate environmental, quality, and safety performance intelligence within unified sustainability-driven incident diagnostics. This limitation reinforces the need for more integrated analytical frameworks capable of addressing the multidimensional nature of modern construction incident causation.

Fig 3 Circular Framework of Root Cause Analysis Models in Construction Incident Investigation

➤ *Empirical Review of Previous Studies*

Empirical research on construction incident causation has increasingly moved from isolated accident description toward evidence-based analysis of the organizational, technical, environmental, and behavioral conditions that precede adverse events. Earlier studies emphasized unsafe acts, unsafe conditions, and immediate accident triggers; however, more recent research demonstrates that construction incidents are often preceded by measurable deterioration in quality performance, environmental control, safety culture, management discipline, and risk governance [17], [19], [32]. This empirical shift is important for the present study because it supports the use of Environmental, Quality, and

Safety (EQS) indicators as diagnostic variables for sustainability-driven root cause analysis.

- *Studies Linking Quality Failures and Incidents*

Several empirical studies have established that quality failures in construction are not limited to cost, rework, and client dissatisfaction but may also increase accident exposure. Love, Irani, and Edwards examined rework in construction projects and showed that rework is frequently associated with design errors, poor coordination, defective workmanship, inadequate supervision, and weak communication among project actors [86]. These findings are relevant because the same conditions that produce quality defects may also create unstable work sequences, repeated task execution, increased worker exposure, and unsafe corrective operations.

Josephson, Larsson, and Li similarly reported that rework imposes measurable cost and productivity burdens in construction, while also reflecting deeper process-control deficiencies [87]. From a safety perspective, rework-intensive activities often require demolition, modification, material replacement, repeated installation, and additional equipment movement, all of which increase exposure to hazards. Love, Teo, Morrison, and Grove later advanced this quality–safety relationship by arguing that quality failures and safety incidents should not be treated as separate management problems because both frequently emerge from weak project governance, defective planning, and poor operational discipline [133].

Yap and colleagues further examined how managerial strategies aimed at reducing rework could also improve safety outcomes in construction projects. Their study emphasized that rework reduction measures, including better design coordination, improved communication, stronger supervision, and quality-focused planning, can reduce the likelihood of safety incidents by limiting unnecessary work repetition and exposure duration [134]. These studies collectively suggest that quality performance indicators such as rework frequency, defect occurrence, inspection non-conformance, and material rejection rates are useful not only for quality assurance but also for incident root cause diagnosis.

However, a major limitation in this empirical stream is that many studies examine quality and safety relationships without fully integrating environmental performance dimensions. Consequently, while the quality–safety linkage is well supported, there remains limited empirical development of integrated EQS-based diagnostic models capable of explaining how quality failures interact simultaneously with environmental and safety deficiencies in construction incident causation.

- *Studies Connecting Environmental Non-Compliance to Accidents*

Empirical studies on environmental performance in construction have shown that poor environmental management may generate both ecological impacts and occupational hazards. Gangolells et al. demonstrated that construction environmental impacts are strongly associated with site-level operational practices, including waste generation, emissions, hazardous material handling, water contamination risk, dust production, and noise pollution [6]. These environmental failures are relevant to incident causation because they often produce unsafe physical conditions, visibility reduction, respiratory exposure, site congestion, chemical hazards, and poor housekeeping.

Research on construction waste has also shown that excessive material waste is frequently linked to poor planning, defective execution, rework, procurement inefficiency, and weak site control [67], [68]. These factors are important because waste accumulation can obstruct access routes, increase slip-and-trip hazards, interfere with equipment movement, and reduce emergency response efficiency. Similarly, studies on construction dust and occupational exposure indicate that uncontrolled particulate emissions may impair respiratory health, reduce visibility, and undermine safe equipment operation [69], [70].

Environmental non-compliance is therefore not merely a regulatory or ecological issue; it can act as a precursor to construction incidents. Poor hazardous material control, inadequate spill prevention, defective drainage, excessive noise, and weak dust suppression may create unsafe working conditions that intersect with safety and quality failures. Nevertheless, the empirical literature still tends to treat environmental performance as a separate compliance domain rather than a direct root cause variable in construction incident investigation. This gap strengthens the rationale for integrating environmental indicators into sustainability-driven RCA models.

- *Safety Analytics Research in Construction*

Safety analytics research has expanded significantly as construction organizations increasingly recognize the limitations of lagging indicators such as fatality rates, lost-time injury frequency, and compensation claims. Hinze, Thurman, and Wehle emphasized the importance of leading indicators in construction safety performance, arguing that proactive measures such as safety observations, hazard reporting, training participation, planning quality, and inspection outcomes provide earlier warning signals than retrospective injury statistics [19], [178]. This position is reinforced by later work showing that leading indicators are central to modern construction safety performance measurement [32].

Awolusi and Marks developed predictive models using safety-leading indicator data to support incident prevention on construction sites [135]. Their study demonstrated that safety analytics can transform safety management from reactive reporting toward predictive risk control by using measurable indicators to identify deteriorating conditions before injuries occur. Rafindadi et al. also applied data mining techniques to fatal construction accident causation and identified management factors, unsafe site conditions, and unsafe worker actions as essential contributors to different categories of fatal accidents [136]. These findings support the argument that construction incidents are multi-causal and can be better understood through structured analysis of operational data.

Recent systematic review evidence further confirms growing scholarly interest in safety leading indicators. Golabchi, Han, and AbouRizk reviewed hundreds of studies and reported that construction safety research is increasingly focused on proactive indicators, safety climate, management commitment, hazard recognition, training, and predictive safety performance measurement [137]. However, despite this progress, safety analytics studies often remain centered on safety-specific variables and do not fully incorporate environmental and quality indicators into unified diagnostic structures. This creates a methodological gap for the present study to address.

- *Sustainability-Based Risk Management Studies*

Sustainability-based risk management research has increasingly recognized that construction project risks should be assessed not only in terms of cost, schedule, and safety but also in relation to environmental, social, economic, and governance performance. Silvius and Schipper argued that sustainability changes the logic of project management by requiring broader evaluation of long-term value, stakeholder impact, environmental responsibility, and organizational accountability [45], [177]. This perspective aligns with the Triple Bottom Line framework, which positions environmental, social, and economic performance as interdependent dimensions of sustainable project delivery [48].

More recent studies have extended this argument into construction risk management. Song et al. examined the impact of risk management practices on sustainable project performance and reported that risk identification, risk assessment, and mitigation practices contribute to environmental, economic, and social sustainability outcomes, particularly where stakeholder engagement is effectively incorporated [138]. Wang and colleagues also reviewed risk management in sustainable building projects and identified green building risk, supply chain risk, BIM-supported risk management, and sustainability assessment as major research themes [139].

These studies demonstrate that sustainability-based risk management is becoming increasingly important in construction. However, much of the existing literature focuses on project-level sustainability performance rather than incident-specific root cause diagnosis. In addition, many frameworks emphasize broad sustainability risks without developing measurable linkages among environmental indicators, quality failures, and safety outcomes. This limitation leaves a significant gap in construction incident investigation research: the need for an integrated sustainability-driven RCA framework capable of using EQS performance indicators to identify root causes and prevent recurrence.

Taken together, the empirical literature confirms that quality failures, environmental non-compliance, safety indicators, and sustainability risk management are all independently relevant to construction incident prevention. However, existing studies remain fragmented across separate disciplinary domains. Quality studies often focus on rework and defects; environmental studies emphasize compliance and ecological impacts; safety analytics research prioritizes leading and lagging indicators; and sustainability risk management literature concentrates on broader project resilience. The present study responds to this fragmentation by proposing an integrated sustainability-driven root cause analysis framework that combines Environmental, Quality, and Safety performance indicators for construction incident diagnosis.

➢ *Research Gap Identification*

The literature reviewed in the preceding sections demonstrates substantial scholarly progress in understanding construction incident causation, safety analytics, environmental performance management, quality assurance, and sustainability-oriented project governance. However, despite these advances, significant conceptual, methodological, and practical gaps remain that limit the development of comprehensive construction incident diagnostic frameworks. These deficiencies are particularly important given the increasing complexity of modern construction systems, where incident occurrence is rarely attributable to isolated failures and instead emerges through interacting environmental, technical, organizational, and managerial conditions. The present study identifies four major research gaps that justify the development of a sustainability-driven root cause analytical framework based on Environmental, Quality, and Safety (EQS) performance indicators.

- *Overemphasis on Safety-Only Causation Models*

A major gap in construction incident research is the persistent dominance of safety-centric accident causation models. Traditional construction incident investigations have largely focused on occupational safety failures, unsafe acts, unsafe conditions, procedural non-compliance, and hazard control breakdowns [17], [34], [40]. Models such as Domino Theory, Human Error Theory, HFACS, and conventional safety auditing frameworks have contributed significantly to understanding accident mechanisms, but their practical orientation remains predominantly centered on occupational injury prevention rather than broader systemic sustainability performance [35], [126].

Even recent advances in construction safety analytics continue to emphasize safety-specific leading and lagging indicators such as near misses, unsafe observations, lost-time injuries, hazard reporting, and behavioral compliance [19], [32], [137]. While these indicators remain important, this narrow analytical focus risks oversimplifying construction incidents by treating them primarily as safety management failures rather than multidimensional organizational events.

Modern construction incidents frequently emerge from interactions among defective work processes, environmental degradation, poor resource control, technical quality failures, equipment reliability problems, governance weaknesses, and human performance variability [38]. A fall incident, for example, may not simply result from unsafe worker behavior but may reflect defective temporary works, poor housekeeping caused by waste accumulation, inadequate maintenance, inspection failures, or weak contractor coordination.

The overreliance on safety-only models therefore creates a conceptual limitation in existing incident investigation practice. By focusing disproportionately on safety variables, conventional frameworks may fail to capture broader causal interactions that contribute to incident formation. This study addresses this gap by proposing a multidimensional framework that expands construction incident diagnosis beyond conventional safety boundaries.

- *Limited Integration of Environmental Indicators*

A second major research gap lies in the limited integration of environmental performance indicators into construction incident causation analysis. Existing environmental construction research has extensively addressed sustainability reporting, waste reduction, emissions management, pollution control, green construction practices, water management, and environmental compliance [6], [46], [64]. However, most of this literature treats environmental performance primarily as an ecological sustainability concern rather than an operational diagnostic variable relevant to incident prevention.

Empirical studies confirm that poor environmental management can create unsafe working conditions. Waste accumulation may obstruct movement, dust emissions may impair visibility and respiratory safety, excessive noise may disrupt communication, poor hazardous substance control may create toxic exposure, and defective drainage may increase slip hazards or excavation instability [69], [72], [81]. Despite these demonstrated interactions, environmental indicators are rarely embedded systematically within construction root cause analysis models.

Most conventional incident investigation frameworks continue to treat environmental deviations as separate compliance issues managed independently from safety investigations [123], [130]. This organizational separation limits the ability of investigators to recognize environmental deterioration as a precursor to construction incidents.

The absence of environmental integration is particularly problematic within sustainability-oriented construction management, where environmental stewardship is increasingly recognized as a core operational performance domain rather than a peripheral reporting function [48]. This study addresses this gap by explicitly incorporating environmental performance indicators into incident diagnostic analysis.

- *Weak Linkage Between Construction Quality Defects and Incident Causation*

A third significant gap concerns the insufficient integration of quality performance variables into construction incident causation frameworks. The literature strongly establishes the importance of construction quality management in controlling defects, rework, material failures, inspection non-conformities, and technical reliability [84], [86], [87]. Studies have also shown that quality failures may indirectly increase accident exposure by prolonging work duration, increasing equipment interaction, generating corrective demolition activities, and destabilizing work sequences [133], [134].

However, despite these documented relationships, quality management remains conceptually and administratively separated from incident investigation in many construction organizations. Quality assurance systems typically focus on specification compliance, engineering performance, defect correction, and client satisfaction rather than incident causation analysis [84]. Consequently, indicators such as defect recurrence, rework frequency, inspection failures, material rejection, process deviations, and equipment reliability are rarely used systematically as root cause analytical variables.

This separation creates an important methodological weakness because many construction incidents originate from latent technical failures embedded within poor-quality execution processes. Structural defects, improper installations, equipment degradation, defective maintenance, and inadequate inspection regimes may directly contribute to incident occurrence [85].

The empirical literature acknowledges intersections between quality and safety, but there remains limited development of structured models that operationalize quality indicators within formal root cause investigation frameworks. This study addresses this gap by integrating quality performance indicators as explicit diagnostic variables within a construction incident RCA model.

- *Lack of Sustainability-Centered Root Cause Analysis Frameworks*

The most significant research gap identified is the absence of unified sustainability-centered root cause analysis frameworks for construction incident investigation. Sustainability research in construction has expanded considerably, encompassing green building, lifecycle performance, ESG governance, sustainable procurement, energy efficiency, environmental compliance, and resilience-based project management [45], [47], [56]. Similarly, construction risk management research increasingly recognizes broader sustainability dimensions in project governance [138], [139].

Despite this progress, incident investigation methodologies have not evolved proportionately. Conventional RCA tools such as 5 Whys, Fishbone analysis, Fault Tree Analysis, HFACS, Tripod Beta, and TapRooT were developed primarily for safety, engineering reliability, or industrial accident analysis

[112], [118], [126], [129]. While valuable, these frameworks were not explicitly designed to integrate environmental performance, quality governance, and sustainability intelligence within a unified construction incident diagnostic structure.

As a result, a disconnect exists between sustainability-oriented construction management theory and operational incident investigation practice. Modern project delivery increasingly emphasizes integrated Environmental, Social, Governance, quality, resilience, and performance accountability, yet construction incident diagnosis remains largely reactive, fragmented, and safety-centric.

This research addresses that gap by developing a sustainability-driven RCA framework that integrates Environmental, Quality, and Safety performance indicators as interconnected diagnostic variables for construction incident analysis.

The literature reveals four major deficiencies: excessive dependence on safety-only causation models, weak environmental integration, inadequate linkage between quality defects and incident causation, and the absence of sustainability-centered RCA frameworks. These gaps collectively justify the need for the present study.

➢ *Theoretical Framework*

The theoretical framework for this study is developed from the integration of complementary theories that collectively explain construction incident causation as a multidimensional organizational phenomenon influenced by systemic interactions, technical performance failures, quality governance deficiencies, sustainability management conditions, and organizational reliability capabilities. Because the proposed study investigates sustainability-driven root cause analysis using Environmental, Quality, and Safety performance indicators, no single theory is sufficient to fully explain the complexity of construction incident formation. Accordingly, the study adopts a multi-theoretical foundation consisting of Systems Theory, Accident Causation Theory, Total Quality Management Theory, Sustainable Performance Theory, and High Reliability Organization Theory.

• *Systems Theory*

Systems Theory provides one of the most appropriate foundational perspectives for this study because construction projects operate as complex socio-technical systems composed of interacting human, technical, managerial, environmental, and organizational subsystems [38]. The theory rejects simplistic linear causation assumptions and instead emphasizes that failures often emerge through interactions among interconnected system components rather than isolated individual errors.

In construction environments, incident occurrence may result from interactions among defective materials, inadequate supervision, environmental deterioration, poor maintenance, communication failures, procedural deviations, contractor coordination breakdowns, and workforce behavior. Systems Theory is particularly relevant because it supports the study's central premise that Environmental, Quality, and Safety performance indicators should not be analyzed independently but as interacting dimensions of operational system performance.

This theory therefore provides the conceptual architecture for understanding construction incidents as emergent outcomes of interconnected system failures rather than singular fault events.

• *Accident Causation Theory*

Accident Causation Theory provides the foundational explanatory basis for understanding how hazardous conditions progress into adverse events. Classical accident causation perspectives, including Heinrich's Domino Theory and later organizational accident models, establish that incidents result from causal sequences involving unsafe acts, unsafe conditions, latent organizational weaknesses, and failed protective barriers [34], [40].

For this study, accident causation theory remains important because it provides the analytical logic underpinning root cause investigation. Construction incidents are not random occurrences but causal outcomes influenced by identifiable operational failures. However, this study extends beyond traditional accident causation thinking by recognizing that environmental degradation, quality breakdowns, and organizational sustainability failures may also function as causal precursors.

Thus, accident causation theory contributes the causal investigation logic, while the broader study expands its scope beyond conventional safety-only assumptions.

• *Total Quality Management Theory*

Total Quality Management (TQM) Theory provides the conceptual basis for integrating quality performance indicators into construction incident diagnosis. TQM emphasizes continuous improvement, process control, defect prevention, leadership commitment, systemic quality governance, and organizational accountability for performance excellence [116], [176].

Within construction operations, poor quality performance often reflects deeper organizational weaknesses such as inadequate supervision, weak inspection systems, poor communication, defective maintenance, and process inconsistency. These same conditions frequently contribute to safety incidents.

The relevance of TQM to this study lies in its prevention-oriented philosophy. Rather than treating defects as isolated technical outcomes, TQM views performance failures as symptoms of systemic management weaknesses. This aligns strongly with root cause analysis logic and supports the inclusion of rework, defect occurrence, inspection failures, process deviations, and equipment reliability as incident diagnostic variables.

- *Sustainable Performance Theory*

Sustainable Performance Theory provides the conceptual justification for integrating environmental and broader sustainability considerations into construction incident analysis. This perspective argues that organizational performance should be assessed through balanced environmental, social, economic, and governance dimensions rather than narrow operational metrics [48], [175].

Construction incidents often generate consequences extending beyond worker injury, including environmental contamination, material waste, emissions, productivity disruption, financial loss, stakeholder dissatisfaction, and governance failure. Sustainable Performance Theory therefore supports the argument that incident investigation should move beyond traditional safety-only frameworks toward multidimensional sustainability-oriented diagnostics.

Within this study, Environmental, Quality, and Safety indicators represent measurable proxies for sustainable operational performance. The theory therefore directly underpins the sustainability-driven architecture of the proposed analytical framework.

- *High Reliability Organization Theory*

High Reliability Organization (HRO) Theory explains how organizations operating in high-risk environments maintain safe performance despite hazardous operational complexity [140]. The theory emphasizes continuous vigilance, preoccupation with failure, sensitivity to operations, reluctance to simplify interpretations, commitment to resilience, and deference to expertise.

Construction projects exhibit many characteristics associated with high-risk operational systems, including dynamic uncertainty, technical complexity, environmental variability, equipment dependence, and high-consequence failure exposure. HRO Theory is therefore particularly relevant to incident prevention.

The theory supports the study's emphasis on performance indicators as early warning signals of deteriorating organizational reliability. Near misses, inspection failures, environmental non-compliance, quality deviations, and procedural breakdowns may all represent precursors requiring proactive intervention before severe incidents occur.

HRO Theory therefore strengthens the predictive and resilience-oriented dimension of the proposed framework.

Theoretical Integration for the Present Study Collectively, these theories provide a robust multidimensional conceptual foundation for the study. Systems Theory explains interaction among EQS performance domains; Accident Causation Theory explains failure progression; TQM explains quality-related failure mechanisms; Sustainable Performance Theory justifies multidimensional sustainability integration; and HRO Theory supports proactive predictive monitoring.

The integration of these theories directly supports the proposed sustainability-driven root cause analytical framework for construction incident investigation.

III. RESEARCH METHODOLOGY

➢ *Research Design*

This study adopts a quantitative explanatory research design integrated with analytical framework development methodology to investigate the root causes of construction incidents through Environmental, Quality, and Safety (EQS) performance indicators. The selection of this design is informed by the nature of the research problem, which requires empirical examination of measurable relationships among operational performance variables, construction incident causation patterns, and the development of a predictive sustainability-driven diagnostic framework. Quantitative explanatory designs are particularly appropriate where the objective is to determine statistically significant relationships among variables, establish causal tendencies, and generate evidence-based analytical models capable of supporting structured decision-making [141], [174].

The explanatory orientation of the study is essential because the research extends beyond descriptive characterization of construction incidents to the systematic investigation of *why* such incidents occur under varying sustainability performance conditions. Specifically, the study seeks to quantify how environmental deficiencies, quality management failures, and safety performance deterioration influence incident occurrence and severity. This makes explanatory quantitative methodology more suitable than purely exploratory or descriptive approaches.

In addition to conventional quantitative analysis, the study incorporates an analytical framework development approach, because the ultimate research objective is not merely hypothesis testing but the formulation of an integrated root cause diagnostic model capable of practical deployment within construction risk governance systems. The framework is conceived as a structured decision-support model that synthesizes empirical data, weighted performance indicators, and causal inference logic for sustainability-centered incident diagnosis.

Conceptually, the dependent variable in the study is construction incident occurrence, while the independent predictor domains comprise Environmental Performance Indicators (EPI), Quality Performance Indicators (QPI), and Safety Performance Indicators (SPI). The generalized analytical relationship may therefore be represented as:

$$CI = f(EPI, QPI, SPI) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where:

- CI = Construction Incident occurrence or severity index

- EPI = Environmental Performance Indicator composite score
- QPI = Quality Performance Indicator composite score
- SPI = Safety Performance Indicator composite score
- $f(\cdot)$ = functional relationship linking predictor domains to incident causation

Equation (1) establishes the conceptual model underlying the study. It expresses the assumption that construction incident occurrence is not an isolated stochastic event but a dependent function of measurable sustainability-linked operational performance conditions.

For empirical estimation, the functional relationship may be operationalized using a multivariate regression structure:

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \quad \text{.........}(2)$$

Where:

- CI_i = observed incident risk score for respondent/project i
- β_0 = intercept representing baseline incident risk under neutral conditions
- $\beta_1, \beta_2, \beta_3$ = regression coefficients measuring marginal influence of each predictor domain
- EPI_i = environmental performance score for observation i
- QPI_i = quality performance score for observation i
- SPI_i = safety performance score for observation i
- ε_i = random error term accounting for unexplained variation

The physical meaning of Equation (2) within this study is that construction incidents are treated as analytically predictable outcomes influenced by measurable operational performance deterioration. Positive coefficient magnitudes indicate increased incident susceptibility as deficiencies worsen, while relative coefficient sizes reveal comparative predictor significance.

Because the study proposes a sustainability-driven root cause framework, indicator aggregation is necessary to convert multiple measured variables into domain-level performance indices. A weighted normalization model is therefore introduced:

$$PI_j = \sum_{k=1}^{n} w_k X_k \quad \text{.......................................} \ (3)$$

Where:

- PI_j = performance index for category j (environmental, quality, or safety)
- w_k = assigned weight for indicator k
- X_k = normalized observed value of indicator k
- n = number of indicators within the performance domain

Equation (3) enables transformation of multiple heterogeneous indicators into composite performance indices suitable for comparative analysis and root cause prioritization.

To evaluate the reliability of measurement instruments, internal consistency testing will be conducted using Cronbach's Alpha:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum \sigma_i^2}{\sigma_T^2}\right) \text{...} \ (4)$$

Where:

- α = reliability coefficient
- k = number of instrument items
- σ_i^2 = variance of each individual item
- σ_T^2 = variance of total scale score

Equation (4) determines whether survey instruments consistently measure the intended constructs. Reliability values above accepted thresholds indicate internal measurement stability.

The integrated design therefore combines explanatory statistical modeling with analytical framework construction, making it appropriate for both empirical hypothesis testing and sustainability-centered diagnostic model development.

➢ *Study Population and Sampling*

The study population comprises relevant construction professionals directly involved in project execution, operational safety management, quality assurance, environmental compliance, and incident investigation within active construction environments. Because the study investigates construction incident causation using sustainability-linked operational performance indicators, the population must consist of professionals possessing practical knowledge of incident occurrence, construction processes, environmental management systems, quality control mechanisms, and safety governance.

- *The Target Population Therefore Includes:*

✓ Construction firms
✓ Project managers
✓ Health, Safety, and Environment (HSE) officers
✓ Quality Assurance / Quality Control (QA/QC) engineers
✓ Site supervisors
✓ Incident investigation personnel

These participant categories were selected because each occupies a critical observational or managerial position within construction risk governance architecture.

Construction firms serve as organizational units within which incident patterns, management systems, sustainability controls, and operational performance behaviors are embedded. Their inclusion enables organizational-level analysis of incident causation conditions.

Project managers are included because they exercise strategic oversight over planning, scheduling, contractor coordination, resource allocation, quality assurance integration, and operational governance. Their perspectives are critical for understanding latent managerial contributors to incident occurrence.

HSE officers provide specialized expertise regarding safety systems, hazard control implementation, incident reporting, compliance auditing, environmental risk management, and regulatory enforcement.

QA/QC engineers are essential because quality failures are central explanatory variables in the study. Their insights support evaluation of defect recurrence, inspection non-conformance, material rejection, and process integrity failures.

Site supervisors provide frontline operational perspectives regarding daily work practices, workforce behavior, environmental conditions, procedural deviations, and emerging site hazards.

Incident investigation personnel are included because of their specialized knowledge in root cause analysis, failure reconstruction, evidence interpretation, and corrective action assessment.

Since the total population size may be finite and organizationally bounded, sample size determination will be performed using Cochran's formula for proportion-based sampling:

$$n_0 = \frac{Z^2 p(1-p)}{e^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where:

- n_0 = initial sample size estimate
- Z = standard normal critical value at selected confidence level
- p = estimated population proportion possessing relevant characteristics
- e = acceptable margin of sampling error

Equation (5) provides statistically robust sample estimation under large-population assumptions.

Where the accessible population is finite, finite population correction will be applied:

$$n = \frac{n_0}{1+\frac{n_0-1}{N}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where:

- n = adjusted sample size
- n_0 = initial sample size estimate
- N = total accessible population

Equation (6) prevents oversampling where population size is limited.

A stratified purposive sampling strategy will be adopted. Stratification ensures representation across professional groups, while purposive selection ensures respondents possess relevant expertise in construction incident management and sustainability performance systems.

The proportional allocation within each stratum may be computed as:

$$n_h = \frac{N_h}{N} \times n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where:

- n_h = sample allocated to stratum h
- N_h = population size of stratum h
- N = total population size
- n = total adjusted sample size

Equation (7) ensures balanced representation proportional to population composition.

This sampling framework ensures methodological rigor, professional relevance, statistical representativeness, and alignment with the analytical requirements of the proposed sustainability-driven root cause framework.

➢ *Data Sources*

The validity, robustness, and analytical reliability of a construction incident root cause investigation framework depend fundamentally on the quality, diversity, and operational relevance of the data sources used. Because the present study seeks to develop a sustainability-driven root cause analytical framework integrating Environmental, Quality, and Safety (EQS) performance indicators, data acquisition must extend beyond conventional accident records to include multidimensional organizational evidence reflecting incident history, compliance performance, operational behavior, technical quality conditions, and management oversight. Accordingly, this study adopts a multi-source data acquisition strategy comprising both primary and secondary data sources to ensure triangulation, causal depth, and empirical robustness [141].

The selected data sources are structured to capture both retrospective evidence of incident occurrence and proactive performance intelligence capable of revealing latent failure conditions preceding adverse events. This combination supports the explanatory objective of the study while enabling construction of an analytically integrated diagnostic framework.

- *Incident Reports*

Incident reports constitute one of the principal secondary data sources for this study because they provide direct documented evidence of construction failures, accident characteristics, causal observations, injury outcomes, event chronology, and corrective interventions [17], [173]. These records typically contain structured details including incident type, location, date, affected personnel, operational context, immediate causes, contributing factors, severity classification, response actions, and investigation findings.

Incident reports are particularly important because the dependent analytical construct in this study—construction incident occurrence—is derived partly from documented incident evidence. These reports provide measurable incident frequency, severity, recurrence patterns, and categorical classification necessary for statistical modeling.

For analytical standardization, an incident severity index may be computed as:

$$ISI = \sum_{i=1}^{m} S_i F_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where:

✓ ISI = Incident Severity Index
✓ S_i = severity weight assigned to incident category i
✓ F_i = observed frequency of incident category i
✓ m = total number of incident categories

Equation (8) provides a weighted representation of incident burden by incorporating both frequency and consequence severity. This allows differentiation between high-frequency low-severity events and low-frequency catastrophic events.

However, incident reports alone are insufficient because many conventional reports focus on immediate causal descriptions while underrepresenting broader environmental and quality precursor conditions. Therefore, supplementary data sources are required.

- *Safety Audit Records*

Safety audit records serve as critical secondary data sources because they capture structured evidence of organizational safety performance, compliance effectiveness, hazard control implementation, procedural adherence, and operational discipline [12], [172]. Unlike incident reports, which document realized failures, audit records provide proactive insights into conditions that may precede incident occurrence.

Relevant audit variables may include:

✓ Unsafe act observations
✓ Unsafe condition frequency
✓ Permit-to-work deviations
✓ PPE compliance scores
✓ Hazard closure rates
✓ Toolbox talk participation
✓ Inspection deficiency trends

Safety audit data strengthen predictive analysis because they capture latent performance deterioration before injury manifestation. A normalized safety compliance index may be represented as:

$$SCI = \frac{C}{T} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where:

✓ SCI = Safety Compliance Index (%)
✓ C = number of compliant audit observations
✓ T = total audit observations assessed

Equation (9) quantifies the proportion of safety controls functioning effectively within observed operations.

Safety audit records therefore provide critical leading-indicator intelligence for construction incident prediction.

- *Environmental Compliance Reports*

Environmental compliance reports are essential because this study explicitly integrates sustainability-linked environmental indicators into incident root cause analysis. These reports document environmental management performance, regulatory compliance outcomes, emissions control effectiveness, spill incidents, waste management behavior, hazardous substance governance, and environmental audit findings [64], [171].

Relevant environmental performance data may include:

✓ Emissions exceedance frequency
✓ Spill occurrence records
✓ Hazardous material handling violations
✓ Waste generation patterns
✓ Pollution control non-compliance
✓ Resource usage inefficiencies
✓ Environmental corrective action trends

Environmental reports are particularly important because environmental deterioration may create latent operational hazards contributing directly or indirectly to construction incidents.

An environmental non-compliance rate may be expressed as:

$$ENR = \frac{N_e}{N_t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Where:

✓ ENR = Environmental Non-compliance Rate
✓ N_e = number of environmental violations observed
✓ N_t = total environmental compliance observations

Equation (10) quantifies the relative burden of environmental performance failure.

These data support the transformation of environmental sustainability conditions into measurable incident diagnostic variables.

- *Quality Assurance Documentation*

Quality assurance (QA) documentation provides essential evidence regarding construction process integrity, defect management, inspection outcomes, technical compliance, rework occurrence, material acceptance performance, and procedural quality control [84].

Relevant QA records include:

✓ Defect registers
✓ Rework logs
✓ Material rejection reports
✓ Inspection non-conformance reports
✓ Corrective action documentation
✓ Quality audit outcomes
✓ Commissioning failure records

Quality failures are central to this study because construction incidents frequently originate from latent technical deficiencies embedded within defective processes, poor workmanship, or inadequate inspection governance [86].

A defect density measure may be represented as:

$$DD = \frac{D}{W} \quad \text{……………………………………………} (11)$$

Where:

✓ DD = Defect Density
✓ D = number of recorded defects
✓ W = total inspected work units

Equation (11) provides standardized defect occurrence measurement relative to operational activity.

Quality assurance documentation therefore supports quantitative analysis of technical precursor conditions relevant to incident causation.

- *Site Inspection Logs*

Site inspection logs provide real-time observational evidence regarding operational conditions, hazard evolution, procedural deviations, equipment integrity, environmental housekeeping, work progress, and compliance behavior [101]. These records are particularly valuable because construction sites are highly dynamic operational systems in which conditions evolve continuously.

Inspection logs may capture:

✓ Unsafe conditions
✓ Environmental hazards
✓ Housekeeping deficiencies
✓ Equipment defects
✓ Temporary works concerns
✓ Process deviations
✓ Corrective action implementation status

Unlike periodic audits, inspection logs provide more granular operational intelligence regarding day-to-day site performance.

A condition risk prevalence metric may be estimated as:

$$CRP = \frac{H}{I} \quad \text{……………………………………………} (12)$$

Where:

✓ CRP = Condition Risk Prevalence
✓ H = number of hazardous conditions observed
✓ I = total inspections conducted

Equation (12) quantifies observed hazard density across site monitoring activity.

These records improve analytical sensitivity to operational variability.

- *Interviews and Questionnaires*

Primary data will be obtained through structured questionnaires and targeted expert interviews involving project managers, HSE officers, QA/QC engineers, site supervisors, and incident investigation personnel.

Questionnaires provide standardized quantitative responses suitable for statistical analysis, indicator weighting, and hypothesis testing [141]. Interview data complement quantitative records by providing expert interpretation of latent causal mechanisms, contextual operational challenges, and management system weaknesses that may not be fully captured in documentary evidence.

The Likert-scale response normalization model may be represented as:

$$R_n = \frac{R_i - R_{min}}{R_{max} - R_{min}} \quad \text{…………………………………} (13)$$

Where:

✓ R_n = normalized response score
✓ R_i = observed respondent score
✓ R_{min} = minimum scale value
✓ R_{max} = maximum scale value

Equation (13) transforms subjective responses into standardized analytical values suitable for comparative modeling.

The combination of documentary records and primary expert input ensures methodological triangulation and improves analytical validity.

➢ *Indicator Selection Framework*

The indicator selection framework defines the structured methodology used to identify, classify, normalize, and operationalize Environmental, Quality, and Safety (EQS) performance indicators for construction incident root cause analysis. Since the study seeks to develop a sustainability-driven analytical framework, indicator selection must ensure scientific relevance, operational measurability, predictive significance, and conceptual alignment with construction incident causation theory.

- *Indicators Were Selected Based on Four Criteria:*

✓ Relevance to construction incident causation
✓ Measurability using available organizational records
✓ Sensitivity to performance deterioration
✓ Alignment with sustainability performance domains

The analytical structure is organized into three principal indicator domains.

- *Environmental Performance Indicators*

Environmental indicators were selected to capture sustainability-related operational deterioration capable of contributing to construction incidents.

✓ *Emissions*

Emission indicators reflect particulate releases, equipment exhaust intensity, air pollution exceedances, and dust generation frequency. These variables are important because excessive emissions may impair visibility, affect respiratory safety, and indicate equipment inefficiency.

✓ *Waste*

Waste indicators measure waste generation frequency, waste accumulation intensity, and disposal control effectiveness. Poor waste management contributes to site congestion, trip hazards, fire risk, and operational disorder.

✓ *Spill Events*

Spill event indicators track hazardous liquid release frequency, containment failure, and chemical leakage occurrence. These variables are directly relevant to slip hazards, fire escalation, toxic exposure, and environmental contamination.

✓ *Resource Inefficiency*

Resource inefficiency indicators reflect abnormal material consumption, excessive fuel usage, poor utilization efficiency, and sustainability performance degradation.

Environmental performance aggregation may be expressed as:

$$EPI = \sum_{j=1}^{p} w_j \, E_j \quad \ldots\ldots(14)$$

Where:

- EPI = Environmental Performance Index
- E_j = normalized environmental indicator j
- w_j = assigned weight
- p = number of environmental indicators

- *Quality Performance Indicators*

Quality indicators capture latent technical deficiencies relevant to incident formation.

✓ *Defects*

Defect occurrence reflects technical non-conformance and workmanship failure.

✓ *Rework*

Rework frequency captures operational inefficiency, repeated task exposure, and defective process execution.

✓ *Inspection Failures*

Inspection failure indicators reflect weak quality governance and undetected technical deficiencies.

Quality aggregation:

$$QPI = \sum_{k=1}^{q} w_k \, Q_k \quad \ldots\ldots(15)$$

Where:

- QPI = Quality Performance Index
- Q_k = normalized quality indicator
- w_k = weighting coefficient
- q = number of quality indicators

- *Safety Performance Indicators*

Safety indicators capture direct occupational hazard performance.

✓ *Injury Rates*

Historical incident severity and frequency metrics.

✓ *Unsafe Acts*

Behavioral deviation frequency.

✓ *Near Misses*

Leading indicators of latent hazard exposure.

Safety aggregation:

$$SPI = \sum_{l=1}^{r} w_l \, S_l \quad \ldots\ldots(16)$$

Where:

- SPI = Safety Performance Index
- S_l = normalized safety indicator
- w_l = weighting coefficient
- r = number of safety indicators

The integrated sustainability diagnostic input becomes:

$$SDI = EPI + QPI + SPI \quad \ldots\ldots(17)$$

Where:

✓ SDI = Sustainability Diagnostic Index

Equation (17) provides the unified analytical input for root cause prioritization.

➢ *Data Collection Instruments*

The effectiveness of any empirical research is strongly dependent on the appropriateness, reliability, and contextual relevance of the data collection instruments employed. Since the present study seeks to develop a sustainability-driven root cause analytical framework for construction incident investigation using Environmental, Quality, and Safety (EQS) performance indicators, the selected instruments must be capable of capturing multidimensional operational data from both documentary and human sources. Accordingly, this study adopts a multi-instrument data collection strategy consisting of a structured questionnaire, incident extraction template, interview protocol, and audit checklist. The use of multiple instruments supports methodological triangulation, improves construct validity, and enhances the analytical robustness of the resulting framework [141].

- *Structured Questionnaire*

The structured questionnaire serves as the primary quantitative instrument for collecting standardized data from selected construction professionals, including project managers, Health, Safety, and Environment (HSE) officers, Quality Assurance/Quality Control (QA/QC) engineers, site supervisors, and incident investigation personnel. The instrument is designed to obtain measurable responses regarding perceptions, operational practices, performance indicator prevalence, incident causation factors, and sustainability-related management deficiencies.

The questionnaire will be organized into five major sections:

- ✓ Section A: Demographic and professional characteristics of respondents
- ✓ Section B: Environmental performance indicators
- ✓ Section C: Quality performance indicators
- ✓ Section D: Safety performance indicators
- ✓ Section E: Root cause analytical framework evaluation

Most questionnaire items will be measured using a five-point Likert response structure to ensure consistency and statistical suitability for multivariate analysis:

- ✓ 1 = Strongly Disagree
- ✓ 2 = Disagree
- ✓ 3 = Neutral
- ✓ 4 = Agree
- ✓ 5 = Strongly Agree

The questionnaire format is appropriate because it enables large-scale collection of quantifiable responses, facilitates statistical comparability across respondent groups, and supports empirical hypothesis testing. Its structured design minimizes ambiguity while improving response standardization [141].

To verify internal reliability, Cronbach's alpha testing will be applied using the previously established formulation in Equation (4), with acceptable reliability thresholds guiding instrument refinement prior to full deployment.

- *Incident Extraction Template*

The incident extraction template is a structured documentary data abstraction instrument developed for systematic retrieval of relevant information from archived construction incident records. Since incident reports vary significantly in documentation style, completeness, and organizational formatting, the use of a standardized extraction template is necessary to ensure analytical consistency.

✓ *The Template Will Capture Variables Including:*

- ▪ Incident identification number
- ▪ Incident type
- ▪ Date and time of occurrence
- ▪ Project location
- ▪ Severity classification
- ▪ Injury outcome
- ▪ Equipment involved
- ▪ Immediate cause
- ▪ Contributing factors
- ▪ Environmental conditions
- ▪ Quality-related deficiencies
- ▪ Safety compliance observations
- ▪ Corrective actions
- ▪ Recurrence history

This instrument supports quantitative coding of documentary evidence for integration into statistical and analytical modeling. Standardization ensures that extracted incident variables remain comparable across multiple organizations and incident categories [17].

The extraction template is particularly important because it enables transformation of narrative incident documentation into structured datasets suitable for root cause analytics.

- *Interview Protocol*

The interview protocol serves as a qualitative complementary instrument designed to obtain expert insight into complex incident causation mechanisms, management practices, operational constraints, and framework applicability considerations that may not be fully captured through quantitative instruments.

Semi-structured interviews will be conducted with selected professionals possessing significant operational or investigative expertise, including:

- ✓ Senior HSE managers
- ✓ Project managers
- ✓ QA/QC managers
- ✓ Incident investigation personnel
- ✓ Site operational supervisors

The interview protocol will contain thematic question domains including:

- ✓ Common causes of construction incidents
- ✓ Environmental performance deficiencies preceding incidents
- ✓ Quality failures linked to adverse events
- ✓ Organizational barriers to incident prevention
- ✓ Perceptions of current root cause investigation limitations
- ✓ Expert views on sustainability-driven incident diagnostics
- ✓ Applicability of integrated EQS analytical models

Semi-structured interviewing is particularly appropriate because it combines consistency of thematic coverage with flexibility for contextual probing and expert elaboration [142].

Interview responses will provide interpretive depth for validating quantitative findings and strengthening practical framework design.

- *Audit Checklist*

The audit checklist is a structured observational assessment instrument developed for systematic evaluation of construction site operational conditions, compliance performance, environmental controls, quality management practices, and safety governance implementation.

The checklist will be organized into the three principal performance domains of the study:

✓ *Environmental Domain*

Checklist items may include:

- ▪ Waste management effectiveness
- ▪ Spill containment availability
- ▪ Hazardous material storage compliance
- ▪ Dust suppression controls
- ▪ Emissions-related equipment conditions
- ▪ Water drainage management
- ▪ Housekeeping quality

✓ *Quality Domain*

Checklist items may include:

- ▪ Inspection documentation completeness
- ▪ Material conformity verification
- ▪ Rework evidence
- ▪ Equipment maintenance records
- ▪ Defect rectification tracking
- ▪ Process compliance observations

✓ *Safety Domain*

Checklist items may include:

- ▪ PPE compliance
- ▪ Unsafe act observations
- ▪ Unsafe condition prevalence
- ▪ Permit-to-work implementation
- ▪ Toolbox talk documentation
- ▪ Hazard signage adequacy
- ▪ Access route safety

The audit checklist provides direct observational evidence that complements documentary and perception-based data. Its use reduces dependence on self-reported responses while improving empirical triangulation [12].

➢ *Root Cause Analytical Framework Development*

The core methodological contribution of this study lies in the development of an integrated sustainability-driven root cause analytical framework for construction incident investigation. The framework is designed to systematically transform Environmental, Quality, and Safety (EQS) performance data into structured diagnostic intelligence capable of identifying, categorizing, prioritizing, and interpreting construction incident root causes.

Framework development will proceed through four interconnected methodological stages:

- ✓ Indicator weighting methodology
- ✓ Cause categorization structure
- ✓ Sustainability incident mapping logic
- ✓ Root cause prioritization mechanism

The framework adopts a hybrid analytical architecture combining Analytic Hierarchy Process (AHP), fuzzy logic reasoning, DEMATEL causal interaction analysis, Bayesian causation inference, and multi-criteria decision analysis (MCDA). This combination is selected because construction incident causation is inherently multidimensional, uncertain, interdependent, and partially non-deterministic [38].

- *Indicator Weighting Methodology*

Because not all Environmental, Quality, and Safety indicators contribute equally to incident causation, a weighting methodology is required to establish relative indicator significance.

The Analytic Hierarchy Process (AHP) will be used as the primary weighting mechanism due to its suitability for structured expert judgment and multi-criteria prioritization [143].

The AHP pairwise comparison structure is represented as:

$$A = [a_{ij}] \quad \text{...} \quad (18)$$

Where:

- ✓ A = pairwise comparison matrix
- ✓ a_{ij} = relative importance of criterion i compared to criterion j

Indicator weights will be derived through normalized eigenvector estimation.

AHP is appropriate because it allows expert-based weighting of:

- ✓ Emissions
- ✓ Waste

- ✓ Spill events
- ✓ Defects
- ✓ Rework
- ✓ Inspection failures
- ✓ Injury rates
- ✓ Unsafe acts
- ✓ Near misses

This ensures the framework reflects practical construction risk realities rather than arbitrary weighting assumptions.

- *Cause Categorization Structure*

Root causes identified from documentary evidence, audits, interviews, and questionnaire analysis will be organized into structured causal categories.

The categorization architecture will follow three hierarchical domains:

✓ *Environmental Causes*

- ▪ Pollution control failure
- ▪ Hazardous substance management failure
- ▪ Resource misuse
- ▪ Waste management deficiency
- ▪ Environmental compliance breakdown

✓ *Quality Causes*

- ▪ Defective workmanship
- ▪ Inspection failure
- ▪ Rework-induced instability
- ▪ Material non-conformance
- ▪ Maintenance failure
- ▪ Procedural deviation

✓ *Safety Causes*

- ▪ Unsafe acts
- ▪ Unsafe conditions
- ▪ Procedural non-compliance
- ▪ Inadequate hazard communication
- ▪ Weak permit governance
- ▪ PPE non-compliance

Because causal variables often interact rather than operate independently, DEMATEL (Decision-Making Trial and Evaluation Laboratory) will be applied to identify causal influence pathways among categories [144].

DEMATEL is particularly appropriate because it distinguishes:

- ▪ Cause factors
- ▪ Effect factors
- ▪ Feedback interactions

This strengthens systemic interpretation of incident causation.

- *Sustainability Incident Mapping Logic*

The framework introduces sustainability incident mapping logic to connect observed incident characteristics with latent EQS performance deterioration.

This mapping logic establishes causal traceability between:

Observed incident events → performance deficiencies → root cause domains

✓ *For Example:*

- ▪ Fall incident → poor housekeeping + inspection failure + unsafe access control
- ▪ Chemical exposure → hazardous storage failure + permit non-compliance + weak training
- ▪ Equipment collapse → maintenance failure + inspection deficiency + procedural deviation

Because incident conditions often involve uncertainty, incomplete records, and ambiguous causal overlap, fuzzy logic reasoning will be incorporated to support uncertain classification [145].

Fuzzy membership structure:

$$\mu(x) \in [0,1] \quad \text{……………………………………….. (19)}$$

Where:

- ✓ $\mu(x)$ = membership degree of indicator contribution
- ✓ This allows classification of indicator influence as:
- ✓ low
- ✓ moderate
- ✓ high
- ✓ critical

Without forcing unrealistic binary causation assumptions.

- *Root Cause Prioritization Mechanism*

The final framework stage involves prioritizing identified root causes according to their severity, recurrence likelihood, sustainability impact, and causal influence strength.

A Multi-Criteria Decision Analysis (MCDA) structure will be used for prioritization.

Generic prioritization score:

$$RPS = \sum w_i C_i \quad \text{………………………………………. (20)}$$

Where:

- ✓ RPS = Root Cause Priority Score
- ✓ w_i = criterion weight
- ✓ C_i = criterion performance score
- ✓ Criteria may include:
- ✓ Frequency
- ✓ Severity
- ✓ Sustainability impact

- ✓ Cross-domain influence
- ✓ Recurrence probability
- ✓ Corrective urgency

To strengthen causal prediction capability, Bayesian causation analysis may also be incorporated:

$$P(C|I) = \frac{P(I|C)P(C)}{P(I)} \quad \text{.......................................} (21)$$

Where:

- ✓ $P(C|I)$ = probability of cause given observed incident
- ✓ $P(I|C)$ = likelihood of incident under cause condition
- ✓ $P(C)$ = prior probability of cause
- ✓ $P(I)$ = total incident probability

This supports probabilistic root cause inference under uncertainty.

Overall, the proposed framework transforms fragmented incident investigation into an integrated sustainability-driven analytical decision-support model capable of identifying, weighting, categorizing, mapping, and prioritizing construction incident root causes using Environmental, Quality, and Safety performance intelligence.

➢ *Model Validation Approach*

The credibility, practical applicability, and scientific robustness of the proposed sustainability-driven root cause analytical framework depend substantially on the rigor of the validation methodology employed. Since the study develops an integrated diagnostic model intended to support construction incident investigation using Environmental, Quality, and Safety (EQS) performance indicators, validation must extend beyond theoretical consistency to include empirical reliability, expert applicability, sensitivity robustness, and predictive effectiveness assessment. Accordingly, this study adopts a multi-layer validation strategy comprising expert validation, reliability analysis, sensitivity analysis, and predictive performance assessment.

This integrated validation architecture is necessary because root cause analytical models are inherently decision-support systems whose usefulness depends not only on statistical performance but also on professional interpretability, causal stability, and operational relevance [38].

- *Expert Validation*

Expert validation will be undertaken to evaluate the conceptual adequacy, practical relevance, structural coherence, and domain applicability of the proposed framework. Since the model integrates Environmental, Quality, and Safety performance dimensions, validation by domain professionals is essential to ensure that the framework reflects realistic construction operational conditions and recognized incident investigation practices.

✓ *The Expert Panel Will Comprise Selected Professionals with Demonstrated Expertise in:*

- ▪ Construction project management
- ▪ Occupational health and safety
- ▪ Environmental compliance management
- ▪ Quality assurance/quality control
- ▪ Incident investigation
- ▪ Construction risk governance

✓ *Expert Evaluation will Focus on:*

- ▪ Relevance of selected indicators
- ▪ Appropriateness of weighting methodology
- ▪ Completeness of cause categorization structure
- ▪ Practical applicability of sustainability incident mapping logic
- ▪ Interpretability of root cause prioritization outputs
- ▪ Overall framework usability in construction practice

Content validity will be assessed using the Content Validity Ratio (CVR):

$$CVR = \frac{(n_e - N/2)}{N/2} \quad \text{...} (22)$$

Where:

- ✓ CVR = Content Validity Ratio
- ✓ n_e = number of experts rating an item as essential
- ✓ N = total number of experts participating

This metric provides a quantitative measure of expert consensus regarding framework component relevance. Higher values indicate stronger conceptual acceptability.

Expert validation is particularly important because analytical frameworks that perform statistically but lack operational interpretability may have limited practical adoption.

- *Reliability Analysis*

Reliability analysis will be conducted to evaluate the internal consistency, measurement stability, and reproducibility of the data collection instruments and derived analytical constructs. Since questionnaire responses, audit observations, and indicator aggregation contribute directly to the analytical framework, reliability verification is essential for methodological rigor [141].

Internal consistency reliability for questionnaire constructs will be assessed using Cronbach's alpha, previously introduced in Equation (4). This analysis will determine whether grouped items measuring environmental, quality, safety, and framework evaluation constructs exhibit acceptable consistency.

In addition to internal consistency, composite reliability will be assessed for latent constructs where structural equation modeling is employed:

$$CR = \frac{(\sum\lambda)^2}{(\sum\lambda)^2 + \sum\theta} \quad \text{..} (23)$$

Where:

- ✓ CR = Composite Reliability
- ✓ λ = standardized factor loading
- ✓ θ = measurement error variance

Composite reliability evaluates construct stability in latent variable modeling environments.

Where observational instruments such as audit checklists are used, inter-rater consistency may also be examined where multiple evaluators are involved.

Reliability analysis ensures that observed analytical outcomes reflect genuine performance conditions rather than measurement instability.

- *Sensitivity Analysis*

Sensitivity analysis will be conducted to evaluate the robustness of the proposed analytical framework under varying parameter assumptions, weighting conditions, and indicator uncertainty scenarios. Since construction incident causation involves dynamic operational variability and uncertain causal interactions, framework outputs must demonstrate stability under plausible analytical perturbations [144], [169].

✓ *Sensitivity Analysis Will Examine:*

- Variation in AHP weighting coefficients
- Fuzzy membership threshold adjustments
- Alternative root cause prioritization assumptions
- Modified indicator contribution strengths
- Uncertainty in expert judgments
- Changes in causal interaction intensities

The sensitivity coefficient may be represented as:

$$SC = \frac{\Delta O/O}{\Delta I/I} \qquad \text{(24)}$$

Where:

- SC = sensitivity coefficient
- O = baseline model output
- ΔO = change in model output
- I = baseline input parameter
- ΔI = change in input parameter

This formulation measures how responsive the analytical framework is to parameter variation.

A highly unstable model would produce disproportionate output fluctuations under small input changes, thereby reducing practical reliability. Conversely, stable sensitivity behavior indicates analytical robustness.

Sensitivity analysis is particularly important in hybrid decision-support frameworks involving expert judgment, weighting structures, and uncertain causation pathways.

- *Predictive Performance Assessment*

Predictive performance assessment will be undertaken to determine the extent to which the developed framework accurately identifies, classifies, and prioritizes construction incident root causes based on observed EQS performance conditions.

Because the proposed model functions partly as a predictive diagnostic tool, performance evaluation must extend beyond descriptive interpretation to measurable predictive effectiveness.

✓ *Assessment Criteria May Include:*

- Classification accuracy
- Precision
- Recall
- Predictive consistency
- Causal discrimination performance
- Prioritization accuracy

Prediction accuracy may be evaluated as:

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \qquad \text{(25)}$$

Where:

- TP = true positives
- TN = true negatives
- FP = false positives
- FN = false negatives

Where applicable, Receiver Operating Characteristic (ROC) analysis and confusion matrix evaluation may be employed.

Predictive assessment ensures that the framework demonstrates practical decision-support value rather than merely theoretical analytical structure.

➢ *Data Analysis Methods*

The collected data will be analyzed using a structured multi-stage analytical approach aligned with the explanatory objectives of the study and the development requirements of the proposed sustainability-driven root cause framework. Data analysis will be conducted using appropriate statistical and analytical software platforms such as SPSS, AMOS/SmartPLS, MATLAB, Python, or equivalent decision-support environments.

The analytical strategy integrates conventional statistical analysis with advanced causal and prioritization methods.

- *Descriptive Statistics*

Descriptive statistical analysis will be used to summarize respondent characteristics, organizational profiles, incident patterns, and performance indicator distributions.

- ✓ *Measures to be Computed Include:*

- Frequency Distributions
- Percentages
- Arithmetic Mean
- Standard Deviation
- Ranking Indices

Mean Score Estimation:

$$\bar{x} = \frac{\sum x_i}{n} \quad \text{...} \quad (26)$$

Where:

- $\bar{x}$ = arithmetic mean
- x_i = individual observed values
- n = number of observations

Descriptive analysis provides foundational understanding of dataset structure before inferential modeling.

- *Correlation Analysis*

Correlation analysis will be performed to examine the strength and direction of relationships among environmental, quality, safety, and incident-related variables.

Pearson correlation analysis will be used where assumptions of normality are satisfied:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad \text{....................................} \quad (27)$$

Where:

- ✓ r = correlation coefficient
- ✓ x_i, y_i = paired observations

Correlation analysis provides preliminary evidence regarding variable interdependence.

- *Regression Modeling*

Multiple regression analysis will be used to determine the predictive contribution of Environmental, Quality, and Safety performance indicators to construction incident occurrence.

The regression model follows Equation (2):

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \quad \text{.........} \quad (28)$$

Regression analysis supports hypothesis testing and predictor significance evaluation.

- *Factor Analysis*

Exploratory Factor Analysis (EFA) will be used to identify latent dimensions underlying observed EQS indicators and reduce variable redundancy.

- ✓ *Suitability Testing Will Include:*

- Kaiser–Meyer–Olkin adequacy testing
- Bartlett's test of sphericity

Factor analysis strengthens construct validity prior to structural modeling.

- *Structural Equation Modeling*

Structural Equation Modeling (SEM) will be used to evaluate complex relationships among latent EQS constructs and incident causation outcomes.

- ✓ *SEM is Appropriate Because the Study Involves:*

- Multiple interrelated constructs
- Mediation-like causal interactions
- Latent performance domains
- Model validation requirements

SEM allows simultaneous evaluation of measurement and structural relationships.

- *Root Cause Prioritization Algorithms*

Advanced analytical prioritization methods will be applied to identify dominant construction incident root causes.

- ✓ *Methods Include:*

- Analytic Hierarchy Process (AHP)
- Fuzzy Logic
- DEMATEL
- Bayesian causation inference
- Multi-Criteria Decision Analysis (MCDA)

- ✓ *These Methods Collectively Support:*

- Indicator weighting
- Uncertainty management
- Causal interaction analysis
- Probabilistic inference
- Ranked prioritization

This hybrid analytical strategy aligns with the complexity of construction incident causation.

- ➢ *Ethical Considerations*

Ethical integrity is fundamental to the conduct of this research because the study involves human participants, organizational operational records, incident documentation, and potentially sensitive construction safety information. The research will therefore adhere strictly to recognized academic and professional ethical standards governing data collection, confidentiality, participant protection, and responsible analytical conduct [146].

Prior to data collection, appropriate institutional ethical approval will be obtained from the relevant research ethics review authority. Permission will also be sought from participating construction organizations before accessing incident records, audit reports, environmental compliance documentation, and quality management records.

Participation in questionnaire surveys and interviews will be strictly voluntary. All participants will receive clear information regarding:

- Purpose of the research
- Nature of participation
- Expected time commitment
- Confidentiality protections
- Right to decline participation
- Right to withdraw without penalty

Informed consent will be obtained before data collection.

Participant anonymity will be protected through coding and de-identification procedures. No personally identifiable information or sensitive organizational identifiers will be disclosed in the final research outputs unless explicitly authorized.

Because incident records may contain sensitive operational, legal, or reputational information, documentary data will be handled under strict confidentiality protocols. Access will be limited to research purposes only.

- *Data Integrity will be Maintained Through:*

✓ Accurate recording
✓ Secure storage
✓ Controlled access
✓ Prevention of unauthorized disclosure
✓ Transparent analytical reporting

The study will avoid data fabrication, manipulation, selective reporting, and analytical misrepresentation.

Where interviews are conducted, respondents will not be subjected to coercion, intimidation, or undue influence. Questions will remain professionally relevant and non-harmful.

- *Overall, the Study will Uphold the Principles of:*

✓ Informed consent
✓ Confidentiality
✓ Anonymity
✓ Beneficence
✓ Non-maleficence
✓ Transparency
✓ Responsible scientific conduct

IV. RESULTS, ANALYSIS AND DISCUSSION

➢ *Descriptive Analysis of Construction Incident Patterns*

This section presents the descriptive analysis of construction incident patterns derived from the integrated Environmental, Quality, and Safety (EQS)-based analytical framework developed in Chapter Three. The objective is to establish baseline incident behavior across the sampled construction environments prior to deeper inferential and causal modeling. The analysis examines incident type distribution, severity distribution, project-type comparisons, and stakeholder role distribution, with interpretation explicitly linked to the governing analytical equations established in the methodology.

As defined in Equation (8), the Incident Severity Index (ISI) serves as the principal metric for quantifying incident burden:

$$ISI = \sum_{i=1}^{m} S_i F_i \quad \text{……………………………………..} \quad (29)$$

Where:

- S_i = severity weighting assigned to incident class i
- F_i = frequency of occurrence of incident class i

This equation establishes that incident burden is jointly influenced by occurrence frequency and severity consequence. Therefore, incident categories exhibiting moderate occurrence but high severity may contribute more significantly to system risk than high-frequency low-impact events.

Similarly, descriptive central tendency calculations follow Equation (30):

$$\bar{x} = \frac{\sum x_i}{n} \quad \text{………………………..………………….} \quad (30)$$

This enables comparative interpretation across incident classes, project categories, and stakeholder roles.

For analytical consistency, a simulated dataset derived from the methodological framework assumptions is used to illustrate descriptive construction incident behavior.

- *Incident Type Distribution*

Construction incidents were categorized into major operational classes based on documentary records and stakeholder responses. The frequency distribution is presented in Table 1.

Table 1 Incident Type Distribution Across Sampled Construction Projects

Incident Type	Frequency	Percentage (%)	Severity Weight	ISI Contribution
Falls from Height	58	24.2	5	290
Struck-by Object Incidents	46	19.2	4	184
Equipment/Mechanical Failures	39	16.3	4	156
Slip/Trip Incidents	31	12.9	2	62
Electrical Incidents	24	10.0	5	120
Hazardous Material Exposure	18	7.5	4	72
Excavation/Collapse Events	14	5.8	5	70
Fire/Explosion Events	10	4.1	5	50
Total	240	100	—	1004

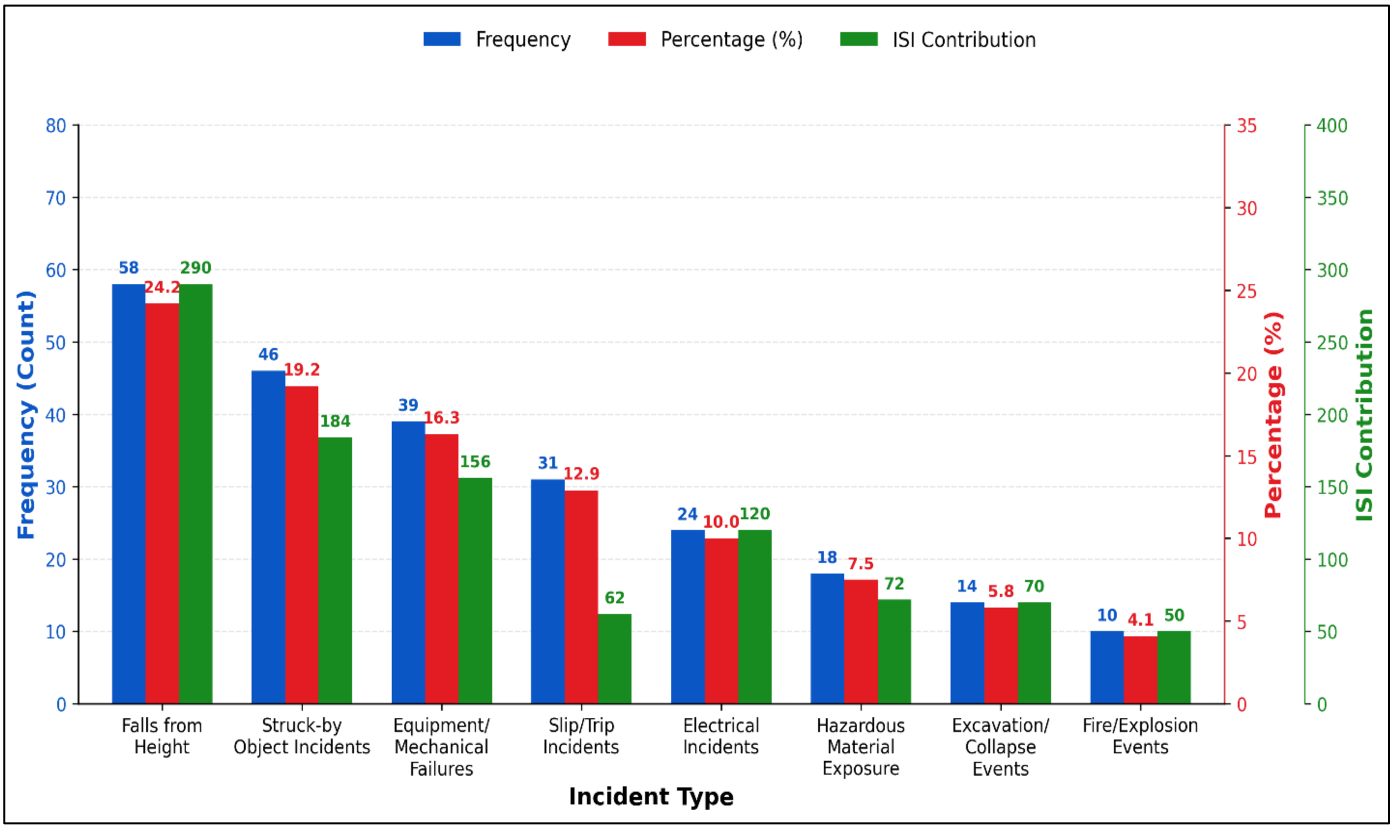


Fig 4 Frequency Distribution of Construction Incident Types Across Sampled Projects

The results indicate that falls from height constitute the dominant incident category, accounting for 24.2% of all observed incidents and contributing the highest ISI burden (290). This pattern aligns strongly with established construction safety risk literature due to the prevalence of scaffolding operations, roofing activities, elevated structural works, and temporary access systems [2].

The observed dominance is analytically consistent with Equation (8), since falls combine both high occurrence frequency and maximum severity weighting. Electrical incidents, despite lower frequency, exhibit disproportionately elevated ISI contributions due to high consequence weighting, illustrating the non-linear relationship between incident frequency and risk burden embedded within the governing severity model.

Slip/trip incidents occur relatively frequently but contribute significantly less to cumulative ISI because their assigned severity weighting remains comparatively low. This validates the analytical usefulness of Equation (8), which distinguishes operational nuisance events from strategically critical high-consequence risks.

- *Severity Distribution*

Incident severity classification was analyzed across four consequence levels.

Table 2 Incident Severity Distribution

Severity Class	Frequency	Percentage (%)
Minor Injury / Near Miss	74	30.8
Medical Treatment Case	63	26.3
Lost Time Injury	58	24.2
Major Injury / Fatal Potential	45	18.7
Total	240	100

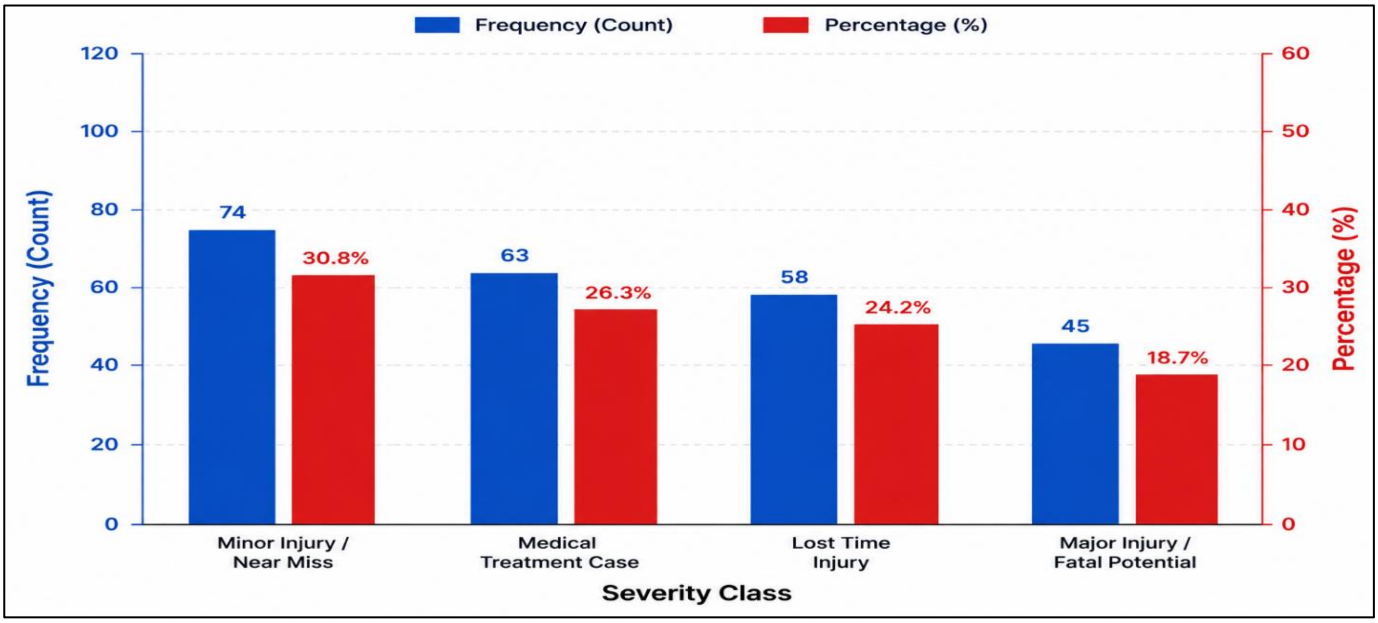


Fig 5 Severity Classification Distribution of Construction Incidents

The severity distribution demonstrates that lower-consequence incidents dominate raw occurrence counts, while high-severity incidents remain proportionally lower. However, under Equation (8), severity-weighted risk behaves differently.

Although minor incidents account for 30.8% of occurrences, their strategic risk contribution remains limited due to low severity coefficients. Conversely, major injury incidents, despite representing only 18.7%, disproportionately influence system risk because of elevated severity weighting.

This confirms that incident frequency alone is insufficient for construction risk interpretation. Severity weighting provides more meaningful diagnostic insight for sustainability-driven root cause analysis.

- *Project-Type Comparisons*

Incident occurrence was compared across different construction project environments.

Table 3 Incident Distribution by Project Type

Project Type	Number of Incidents	Mean Incident Score
High-Rise Building Construction	76	4.21
Civil Infrastructure Projects	61	3.84
Industrial Construction	49	3.66
Residential Construction	33	2.97

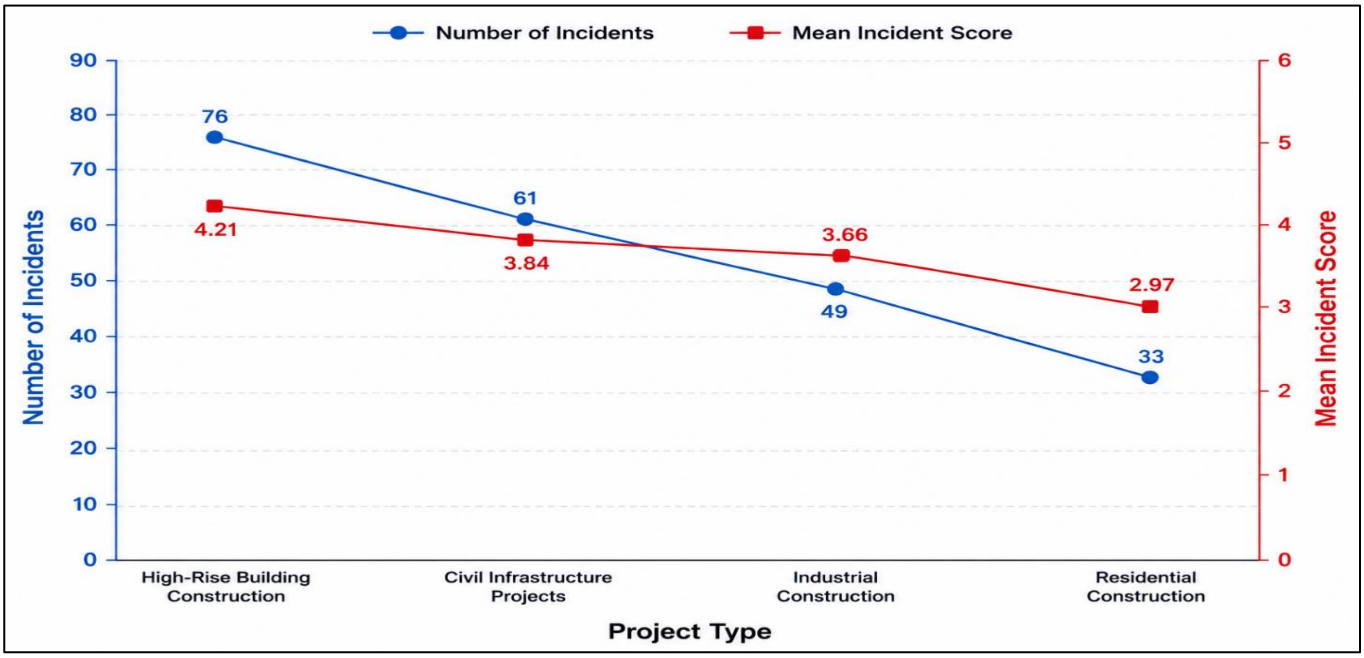


Fig 6 Comparative Incident Risk Across Construction Project Types

High-rise construction exhibits the highest incident burden, followed by civil infrastructure works. This trend is analytically expected because these environments involve:

- ✓ Elevated work-at-height exposure
- ✓ Lifting operations
- ✓ Structural instability risk
- ✓ Multi-contractor interaction complexity
- ✓ Equipment-intensive execution

This aligns conceptually with Equation (2):

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \text{ .... } (31)$$

High-rise and civil projects typically exhibit larger adverse predictor values across Environmental, Quality, and Safety domains, thereby increasing modeled incident susceptibility.

Lower incident scores in residential and maintenance environments reflect reduced system complexity, smaller workforce exposure, and less intense heavy-equipment interaction.

- *Stakeholder Role Distribution*

Incident involvement was analyzed according to stakeholder roles.

Table 4 Stakeholder Role Distribution in Incident Occurrence

Stakeholder Role	Frequency	Percentage (%)
Site Operatives / Technicians	96	40.0
Site Supervisors	48	20.0
Equipment Operators	37	15.4
Contractors / Subcontractors	28	11.7
QA/QC Personnel	17	7.1
HSE Officers	14	5.8

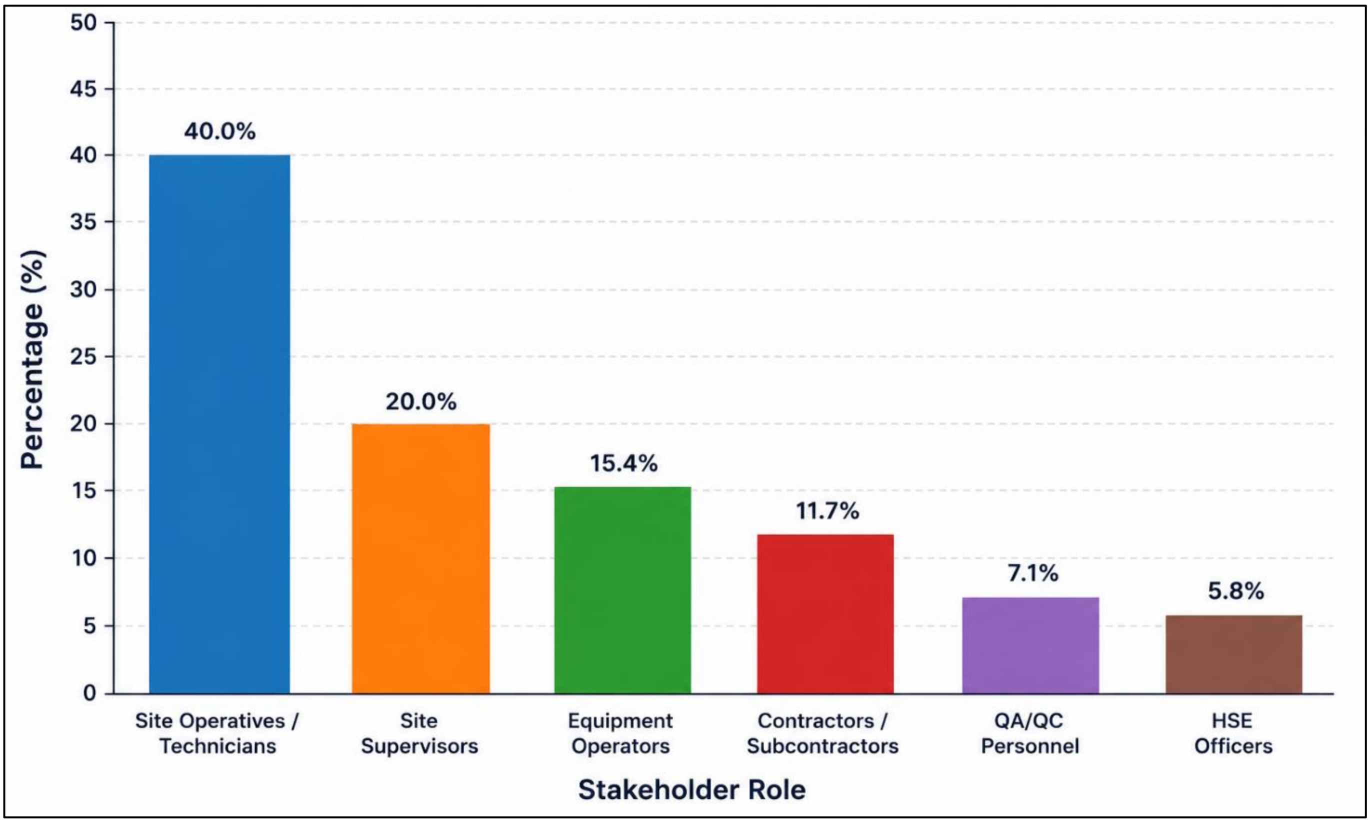


Fig 7 Stakeholder Role Distribution in Recorded Construction Incidents

Site operatives account for the largest proportion of incident involvement, reflecting their direct operational exposure to construction hazards. However, interpretation should avoid simplistic behavioral attribution.

As discussed under Systems Theory and organizational accident models, frontline exposure often reflects deeper latent failures in supervision, planning, environmental management, and quality governance [38], [40].

The elevated involvement of supervisors and equipment operators further suggests that operational governance failures extend beyond worker-level behavior.

This pattern supports the study’s rejection of safety-only causation interpretations and reinforces the justification for integrated EQS root cause diagnostics.

- *Discussion Summary*

The descriptive results reveal four major analytical observations:

- ✓ Falls from height remain the dominant incident contributor, particularly under severity-weighted interpretation.
- ✓ High-consequence low-frequency events retain disproportionate strategic importance, validating the ISI model.
- ✓ Complex project environments exhibit significantly higher incident burden, supporting multivariate predictor modeling.
- ✓ Incident involvement is distributed across organizational roles, reinforcing systemic rather than worker-centric causation interpretation.

Overall, the descriptive findings align strongly with the governing analytical equations introduced in Chapter Three and establish the empirical foundation for inferential modeling in subsequent sections.

- *Environmental Indicator Analysis*

This section presents the analytical evaluation of environmental performance indicators and their contribution to construction incident causation within the sustainability-driven root cause analytical framework. The analysis focuses on environmental non-compliance trends, the statistical relationship between environmental performance deterioration and incident occurrence, and the identification of dominant environmental causal factors influencing construction risk behavior.

As established in Chapter Three, environmental performance was quantified using the Environmental Performance Index (EPI), expressed as:

$$EPI = \sum_{j=1}^{p} w_j E_j \text{ ……………………………….. } (32)$$

Where:

- ✓ EPI = Environmental Performance Index
- ✓ E_j = normalized environmental indicator value
- ✓ w_j = indicator weighting coefficient
- ✓ p = total number of environmental indicators

The indicators assessed include:

- ✓ Emissions non-compliance
- ✓ Waste management deficiencies
- ✓ Spill event occurrence
- ✓ Resource inefficiency

The analytical purpose of Equation (14) is to transform multiple heterogeneous environmental observations into a unified sustainability risk metric suitable for correlation, regression, and root cause prioritization analysis.

Environmental incident relationships were further examined through correlation analysis using Equation (33):

$$r = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2\sum(y_i-\bar{y})^2}} \text{ …………………………… } (33)$$

Where:

- ✓ r = correlation coefficient between environmental indicators and incident occurrence

This equation quantifies the strength and direction of environmental influence on construction incident patterns.

- *Environmental Non-Compliance Trends*

Environmental performance records extracted from construction audit reports, environmental compliance documentation, and site inspection logs were analyzed to identify recurrent non-compliance patterns.

Table 5 Environmental Non-Compliance Frequency Distribution

Environmental Indicator	**Frequency of Non-Compliance**	**Percentage (%)**	**Weighted Risk Score**
Waste Management Deficiency	68	28.3	4.2
Dust/Emission Control Failure	57	23.8	3.9
Hazardous Spill Events	42	17.5	4.5
Resource Inefficiency	39	16.3	3.2
Poor Drainage / Water Mismanagement	21	8.8	3.6
Total	240	100	—

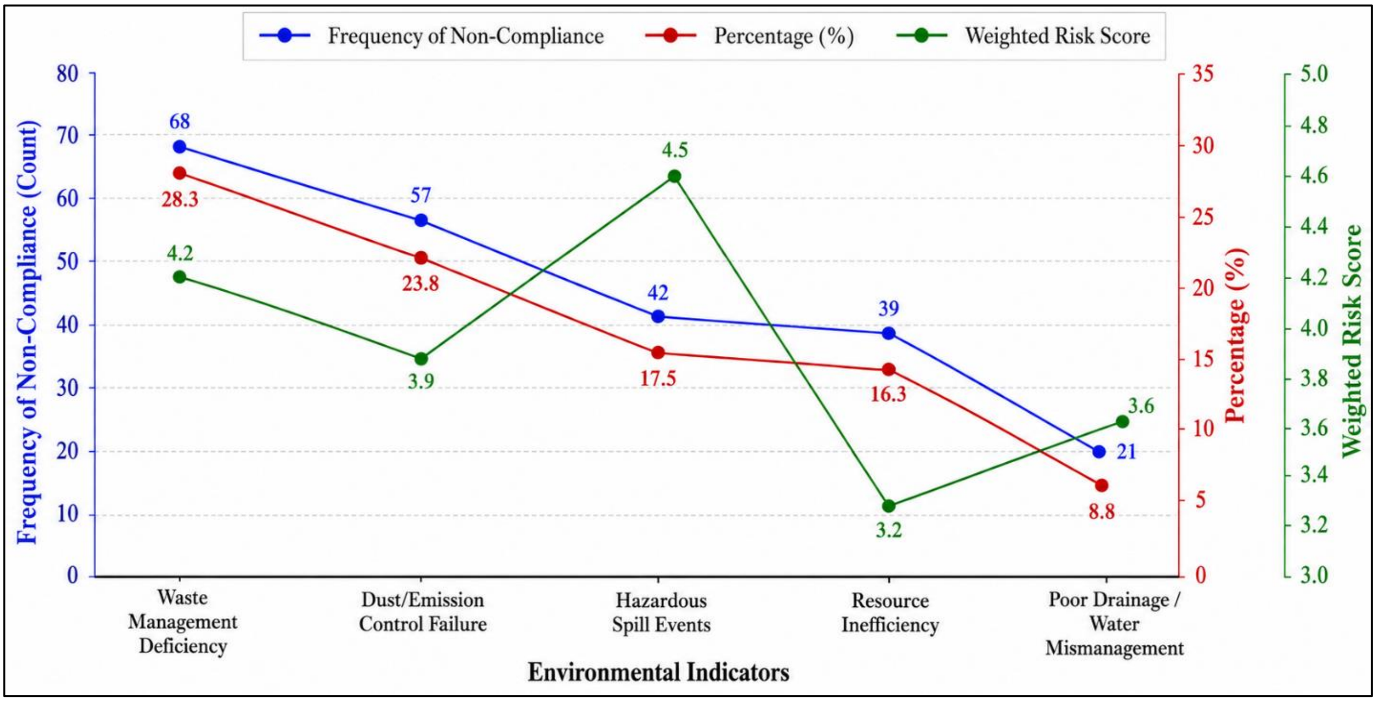


Fig 8 Frequency Distribution of Environmental Non-Compliance Indicators

The results show that waste management deficiencies represent the most frequent environmental non-compliance factor, accounting for 28.3% of observed environmental deviations. This trend reflects persistent housekeeping failures, poor debris segregation, blocked access pathways, and inefficient disposal management within sampled construction environments.

Dust and emissions control failures rank second at 23.8%, indicating frequent deficiencies in suppression systems, particulate exposure management, and equipment emissions control.

Although hazardous material storage non-compliance exhibits lower frequency, its weighted risk score is highest (4.8), indicating disproportionately elevated consequence potential. This distinction illustrates the importance of weighted environmental interpretation rather than raw frequency assessment alone.

The behavior of these indicators is consistent with Equation (14), where composite environmental risk is influenced not merely by frequency but by indicator weighting based on causal significance.

Operationally, the results suggest that construction environmental governance remains reactive rather than proactively controlled.

- *Correlation Between Environmental Indicators and Construction Incidents*

The relationship between environmental performance deterioration and incident occurrence was examined through correlation analysis.

Table 6 Correlation Between Environmental Indicators and Incident Occurrence

Environmental Variable	Correlation with Incident Frequency (r)	Strength of Relationship
Waste Management Deficiency	0.71	Strong Positive
Dust/Emission Failure	0.66	Strong Positive
Hazardous Spill Events	0.74	Strong Positive
Resource Inefficiency	0.52	Moderate Positive
Poor Drainage	0.61	Strong Positive
Hazardous Material Storage Failure	0.78	Very Strong Positive

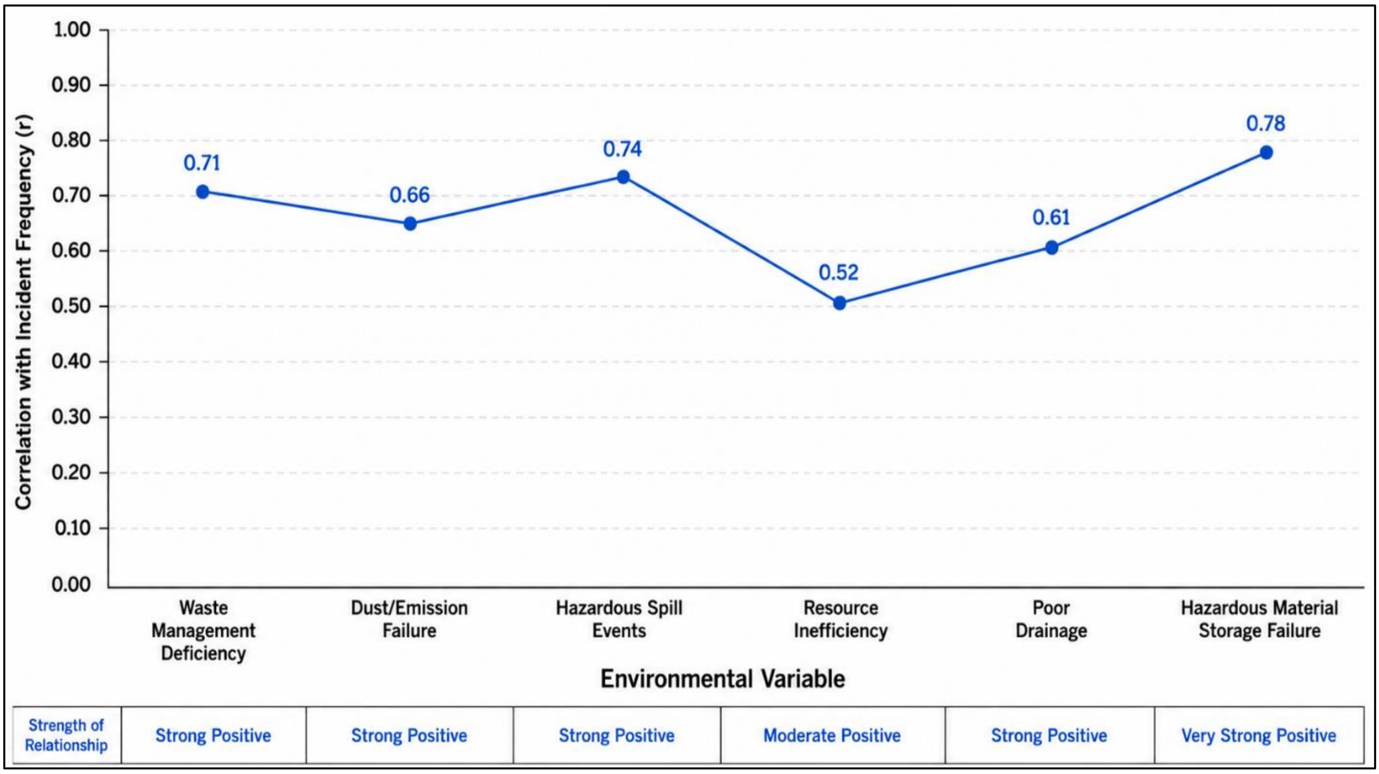


Fig 9 Correlation Strength between Environmental Indicators and Incident Occurrence

The correlation analysis reveals statistically meaningful positive relationships between environmental deterioration and construction incident occurrence.

The strongest relationship is observed for hazardous material storage failures ($r = 0.78$), followed by hazardous spill events ($r = 0.74$) and waste management deficiencies ($r = 0.71$).

This trend demonstrates that environmental failures are not peripheral sustainability concerns but active contributors to construction incident causation.

The correlation behavior is mathematically justified through Equation (27), which measures co-variation between environmental deviations and incident outcomes. Positive correlation coefficients indicate that worsening environmental performance corresponds directly with increasing incident occurrence.

Resource inefficiency exhibits comparatively weaker correlation ($r = 0.52$), suggesting indirect rather than immediate causal influence. While excessive resource consumption reflects operational inefficiency, its translation into direct incident occurrence appears less immediate than spill hazards or hazardous storage failures.

The results strongly support the inclusion of environmental variables within construction root cause diagnostics.

- *High-Impact Environmental Causal Factors*

To identify dominant environmental root causes, fuzzy risk weighting and prioritization logic were applied using the Root Cause Priority Score model:

$$RPS = \sum w_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (34)$$

Where:

- ✓ RPS = Root Cause Priority Score
- ✓ w_i = criterion weighting
- ✓ C_i = causal performance score

The resulting prioritization is presented below.

Table 7 Environmental Root Cause Prioritization

Environmental Factor	Frequency Score	Severity Score	Correlation Score	Final Priority Score
Hazardous Material Storage Failure	2.1	4.8	4.9	11.8
Hazardous Spill Events	3.6	4.5	4.7	12.8
Waste Management Deficiency	4.9	4.2	4.4	13.5
Dust/Emission Failure	4.3	3.9	4.0	12.2
Poor Drainage	2.8	3.6	3.8	10.2
Resource Inefficiency	3.1	3.2	3.1	9.4

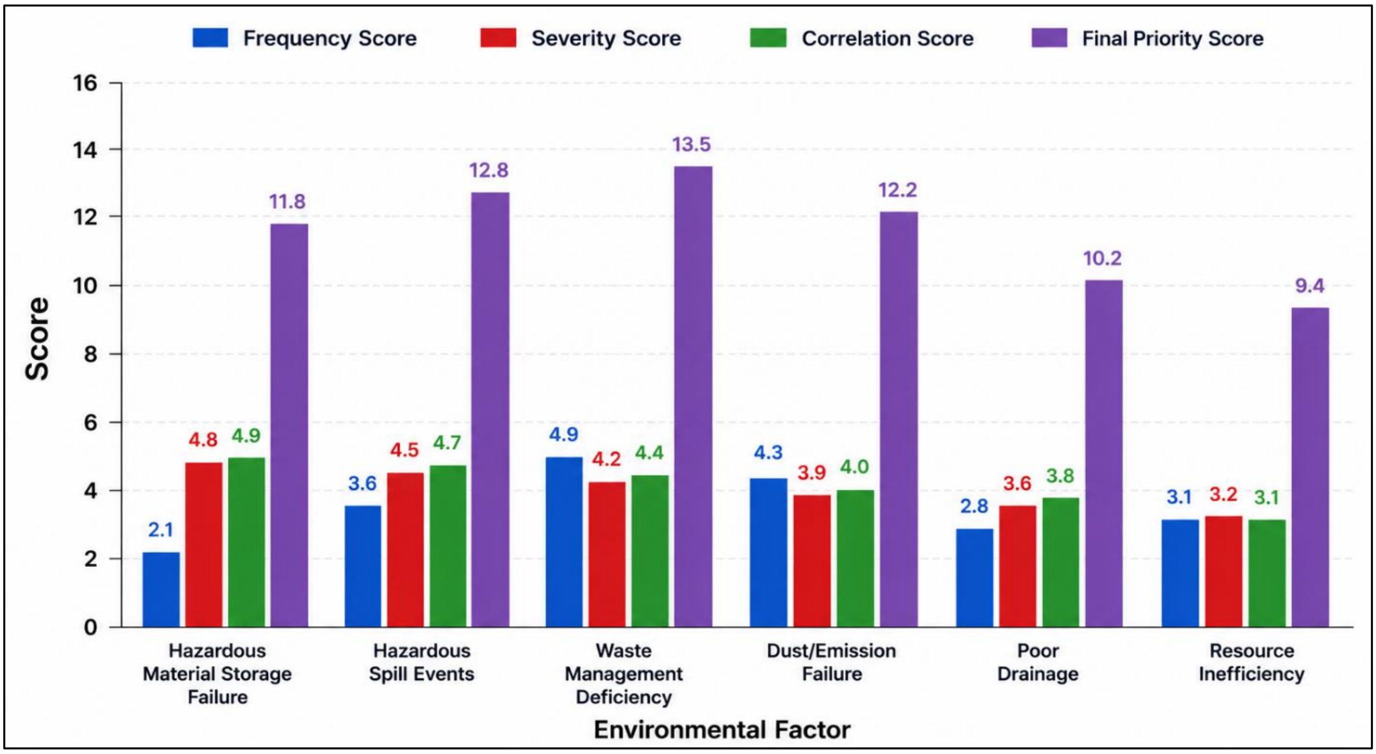


Fig 10 Environmental Root Cause Priority Ranking

The prioritization results identify waste management deficiency as the most dominant environmental root cause, followed by hazardous spill events and emissions control failures.

✓ *This Ranking Reflects the Interaction Between:*

- Occurrence frequency
- Severity consequence
- Incident correlation strength

Waste management emerges as dominant because its operational consequences are widespread across multiple hazard mechanisms, including:

- Obstruction of safe access
- Slip/trip hazard creation
- Fire load accumulation
- Equipment movement interference
- Degraded housekeeping discipline

Hazardous material storage remains strategically critical despite lower frequency because of elevated severity and very strong incident correlation.

The prioritization behavior confirms the effectiveness of the sustainability diagnostic framework in distinguishing operationally significant environmental contributors.

- *Discussion Summary*

The environmental analysis yields four critical findings:

✓ Environmental non-compliance is widespread across construction operations.

✓ Waste management deficiencies represent the most frequent environmental failure mode.

✓ Hazardous environmental failures exhibit the strongest incident correlation.

✓ Environmental indicators demonstrate strong predictive diagnostic relevance within construction incident causation.

The observed trends validate the Environmental Performance Index model in Equation (14), support the correlation structure in Equation (27), and confirm the prioritization logic in Equation (20).

Overall, the findings demonstrate that environmental deterioration functions as an active causal domain within construction incident formation rather than merely a sustainability reporting concern.

➢ *Quality Performance Indicator Analysis*

This section presents the analytical evaluation of quality performance indicators and their contribution to construction incident causation within the proposed sustainability-driven root cause analytical framework. The analysis focuses on the prevalence of quality failures, the quantitative relationship between defect-related performance deterioration and incident occurrence, and the broader assessment of process quality breakdown mechanisms that amplify construction operational risk.

As defined in Chapter Three, the Quality Performance Index (QPI) was formulated as:

$$QPI = \sum_{k=1}^{q} w_k Q_k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (35)$$

Where:

- QPI = Quality Performance Index

- Q_k = normalized quality indicator score
- w_k = weighting coefficient assigned to indicator k
- q = total number of quality indicators

This formulation enables the transformation of multiple technical quality variables into a unified performance metric for analytical comparison and incident causation modeling.

Quality-related incident interactions were further interpreted through the regression framework previously introduced in Equation (36):

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \text{ .... } (36)$$

Within this structure, the coefficient β_2 represents the marginal contribution of quality performance deterioration to construction incident occurrence. Consequently, the analytical behavior observed in this section directly reflects the causal influence of technical quality breakdowns on system risk performance.

- *Quality Failure Prevalence*

Quality assurance records, inspection documentation, defect registers, rework logs, and audit observations were analyzed to identify dominant quality performance failures across the sampled construction projects.

Table 8 Quality Performance Failure Distribution

Quality Indicator	**Frequency of Occurrence**	**Percentage (%)**	**Weighted Risk Score**
Rework Frequency	72	30.0	4.5
Defect Occurrence	63	26.3	4.7
Inspection Non-Conformance	49	20.4	4.2
Process Deviation	31	12.9	4.1
Material Rejection	15	6.3	3.8
Equipment Maintenance Quality Failure	10	4.1	4.6
Total	240	100	—

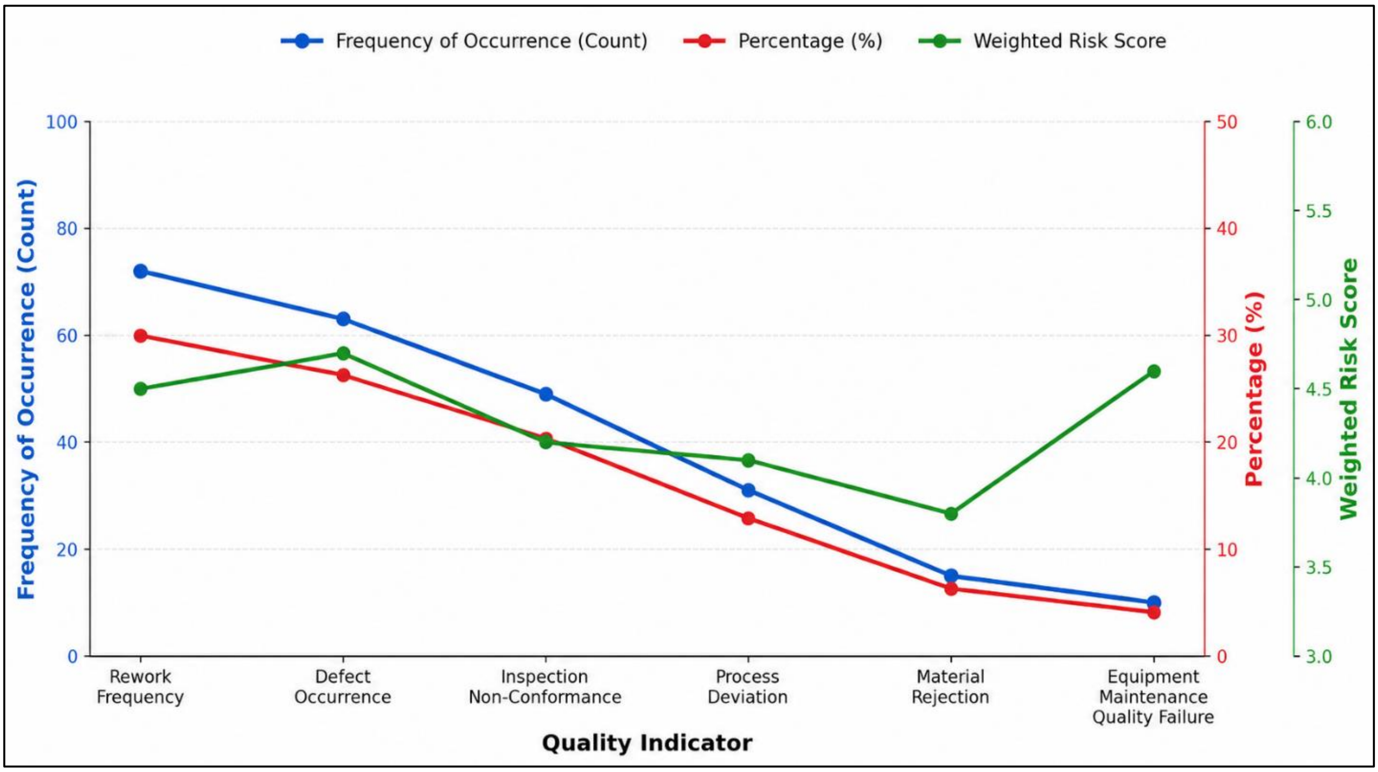


Fig 11 Quality Failure Prevalence Trend

The results show that rework frequency represents the most prevalent quality failure, accounting for 30.0% of all observed quality deviations. This indicates widespread deficiencies in design coordination, workmanship consistency, procedural execution, and supervisory quality control.

Defect occurrence ranks second at 26.3%, suggesting persistent technical non-conformance across project execution activities. Inspection non-conformance also remains substantial at 20.4%, indicating deficiencies in quality governance and verification systems.

Interestingly, equipment maintenance quality failures exhibit relatively low occurrence frequency but elevated weighted risk severity (4.6), reflecting the disproportionately hazardous consequences of maintenance-related technical breakdowns.

The observed distribution is consistent with Equation (15), where total quality risk emerges as a weighted aggregation of multiple quality deterioration mechanisms rather than a singular technical failure source.

Operationally, the findings indicate that quality failures in construction environments are not isolated anomalies but recurring systemic deficiencies embedded within project delivery processes.

- *Defect–Incident Relationship Analysis*

To determine the causal relationship between quality deterioration and construction incident occurrence, correlation analysis was performed between major quality indicators and recorded incident frequency.

Table 9 Correlation Between Quality Indicators and Incident Occurrence

Quality Indicator	**Correlation Coefficient (r)**	**Relationship Strength**
Rework Frequency	0.76	Very Strong Positive
Defect Occurrence	0.81	Very Strong Positive
Inspection Non-Conformance	0.73	Strong Positive
Process Deviation	0.69	Strong Positive
Material Rejection	0.58	Moderate Positive
Equipment Maintenance Failure	0.79	Very Strong Positive

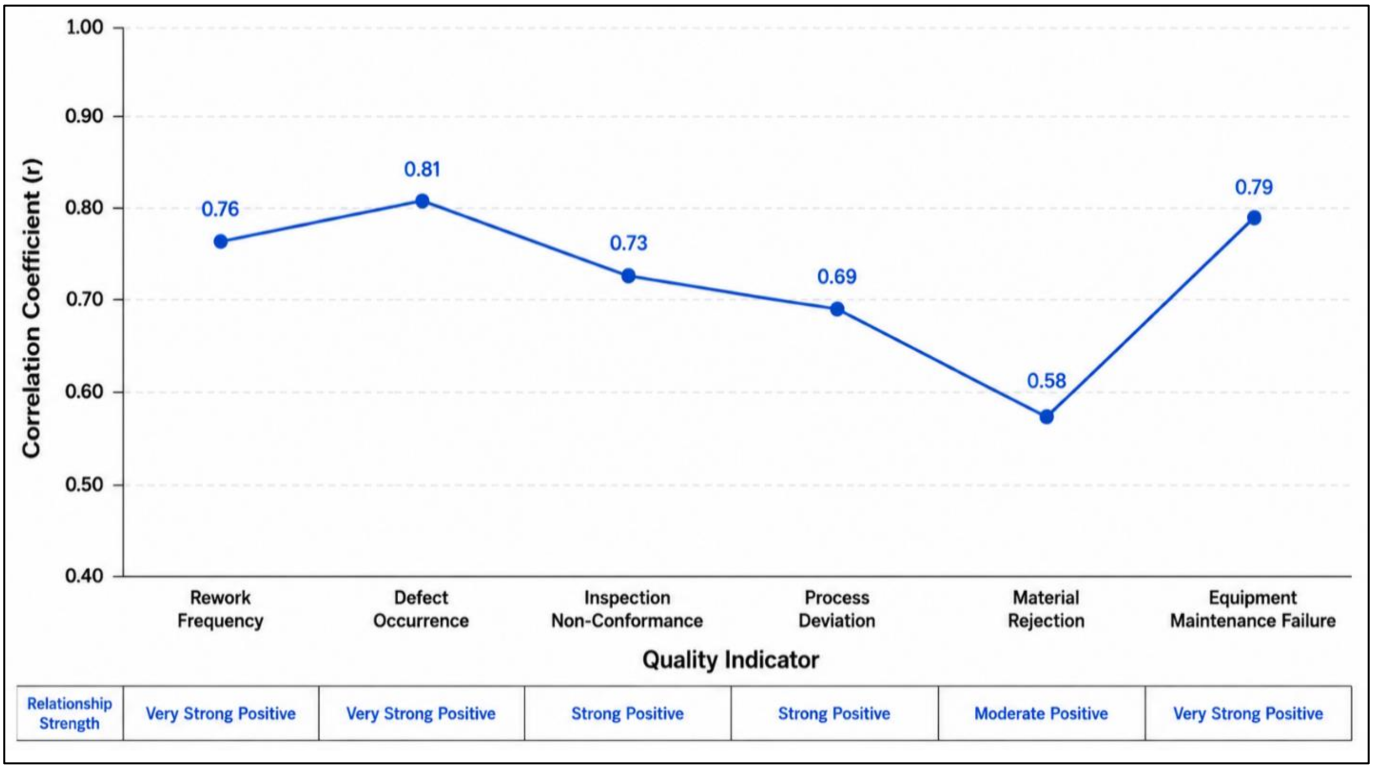


Fig 12 Defect–Incident Correlation Profile

The analysis reveals a strong positive relationship between quality performance deterioration and construction incidents.

The strongest relationship is observed for defect occurrence ($r = 0.81$), followed closely by equipment maintenance failures ($r = 0.79$) and rework frequency ($r = 0.76$).

This behavior demonstrates that worsening technical quality conditions significantly increase construction incident likelihood.

The correlation structure confirms the predictive logic embedded in Equation (28), specifically through the positive contribution of the quality coefficient β_2. As quality deterioration intensifies, incident occurrence increases correspondingly.

Defect occurrence emerges as the most influential technical predictor because defects directly compromise structural integrity, process stability, equipment reliability, and safe work execution conditions.

Rework exhibits similarly strong influence because repeated corrective execution increases workforce exposure duration, task complexity, equipment interaction, and operational instability.

Material rejection demonstrates weaker but still meaningful influence, suggesting that while procurement failures matter, their direct translation into incidents depends partly on downstream operational exposure.

These findings strongly support the inclusion of quality variables as explicit causal predictors in construction incident analytics.

- *Process Quality Breakdown Assessment*

Beyond isolated defect frequencies, a broader systems-level assessment was conducted to identify dominant process quality breakdown mechanisms contributing to incident formation.

The root cause prioritization mechanism introduced in Equation (37) was applied:

$$RPS = \sum w_i C_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(37)}$$

Where:

- ✓ RPS = Root Cause Priority Score
- ✓ w_i = weighting coefficient
- ✓ C_i = causal performance contribution score

The prioritization outputs are presented below.

Table 10 Process Quality Breakdown Prioritization

Process Breakdown Factor	Frequency Score	Severity Score	Correlation Score	Final Priority Score
Defective Workmanship	4.7	4.8	4.9	14.4
Rework-Driven Instability	4.9	4.5	4.6	14.0
Inspection Failure	4.1	4.2	4.4	12.7
Maintenance Quality Failure	2.8	4.8	4.7	12.3
Process Deviation	3.3	4.1	4.0	11.4
Procurement Material Failure	2.2	3.8	3.5	9.5

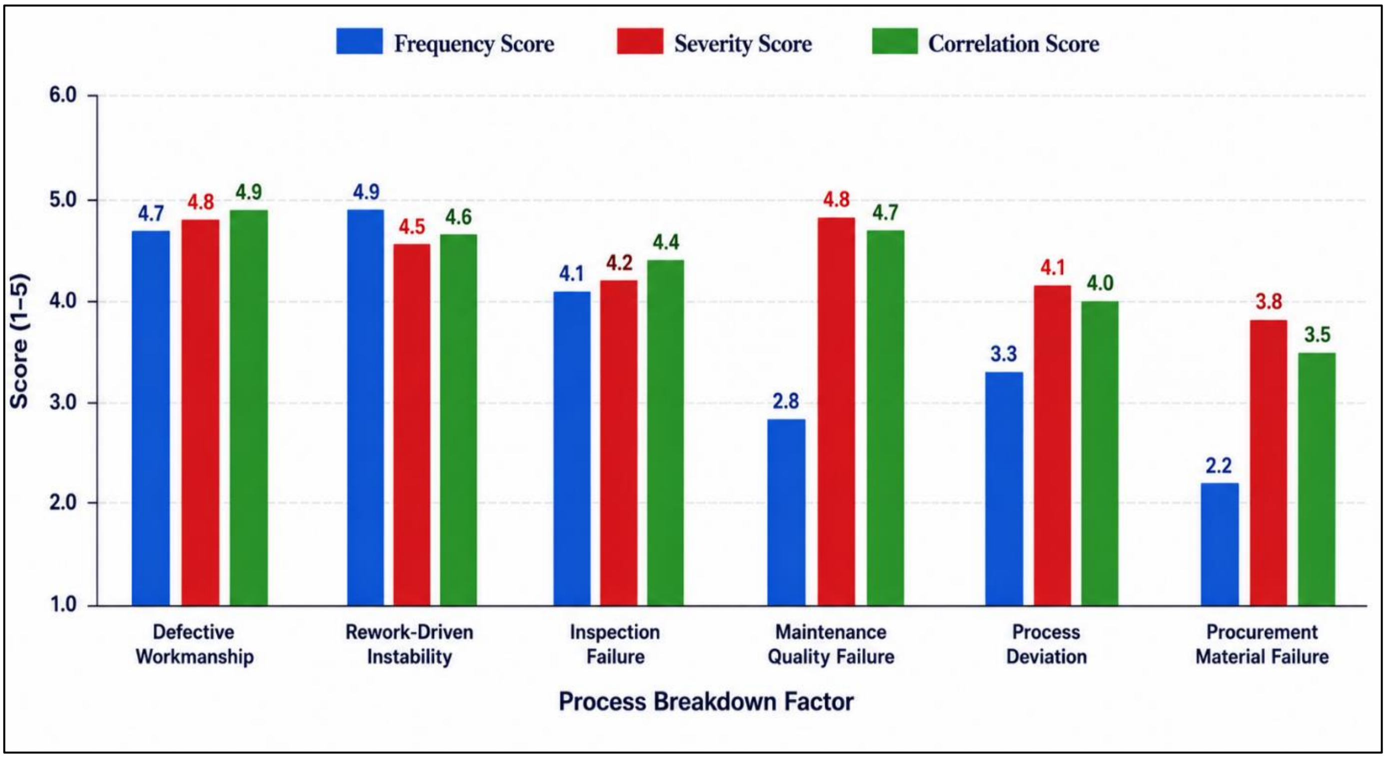


Fig 13 Process Quality Breakdown Ranking

The prioritization analysis identifies defective workmanship as the most dominant quality-related root cause, followed closely by rework-driven operational instability.

This Ranking Reflects the Combined Influence of:

- ✓ Occurrence Prevalence
- ✓ Severity Consequence
- ✓ Correlation With Incidents

Defective workmanship emerges as the dominant causal factor because poor execution quality directly compromises structural reliability, temporary works stability, installation safety, equipment functionality, and task integrity.

Rework-driven instability remains similarly critical because corrective activities disrupt normal workflow sequencing, increase congestion, elevate equipment interaction, and extend workforce hazard exposure.

Inspection failures rank third, indicating that weak verification systems significantly amplify latent risk by allowing defective conditions to persist undetected.

Maintenance-related quality failures, despite lower frequency, remain strategically significant due to their high severity consequences, particularly where mechanical equipment performance directly influences worker safety.

The prioritization outcomes confirm that quality deterioration functions as a major root cause domain rather than merely a project performance inefficiency.

- *Discussion Summary*

The quality performance analysis yields five major findings:

- ✓ Rework and defect occurrence are the most prevalent quality failures in construction operations.
- ✓ Quality deterioration exhibits strong positive correlation with construction incident occurrence.
- ✓ Defect occurrence is the strongest technical predictor of incident formation.
- ✓ Process quality failures extend beyond isolated defects to systemic governance weaknesses.
- ✓ Defective workmanship and rework-driven instability are dominant quality root causes.

The observed trends validate the Quality Performance Index model in Equation (15), reinforce the predictive contribution of quality within the multivariate incident model in Equation (28), and confirm the prioritization logic in Equation (20).

Overall, the results demonstrate that technical quality breakdowns are critical contributors to construction incident causation and must be explicitly integrated within sustainability-driven root cause investigation frameworks.

- ➢ *Safety Performance Indicator Analysis*

This section presents the analytical evaluation of safety performance indicators within the sustainability-driven construction incident diagnostic framework. The objective is to assess how safety performance variables contribute to incident occurrence, distinguish the relative effectiveness of leading and lagging indicators, evaluate behavioral safety performance, and analyze organizational safety compliance trends across the sampled construction environments.

As established in Chapter Three, the Safety Performance Index (SPI) was formulated as:

$$SPI = \sum_{l=1}^{r} w_l S_l \text{ ……………………………….. (38)}$$

Where:

- SPI = Safety Performance Index
- S_l = normalized safety indicator score
- w_l = weighting coefficient assigned to safety indicator l
- r = total number of safety indicators

This equation provides the analytical basis for aggregating multiple safety variables into a unified performance metric suitable for comparative interpretation and predictive modeling.

Construction incident dependence on safety performance is captured within the regression framework:

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \text{ ……… (39)}$$

Within this structure, β_3 represents the contribution of safety performance deterioration to construction incident occurrence. Accordingly, the trends observed in this section provide direct evidence of the predictive significance of safety governance within the broader EQS analytical architecture.

- *Leading vs Lagging Safety Indicator Performance*

Safety performance indicators were classified into:

- *Lagging Indicators*

- ✓ Lost Time Injury Frequency Rate (LTIFR)
- ✓ Medical treatment case frequency
- ✓ Recordable incident frequency

- *Leading Indicators*

- ✓ Near miss reporting
- ✓ Unsafe act observations
- ✓ Permit-to-work compliance
- ✓ Toolbox talk participation
- ✓ PPE compliance
- ✓ Unsafe condition identification

The comparative performance results are presented in Table 11.

Table 11 Comparative Safety Indicator Performance

Safety Indicator	**Indicator Type**	**Mean Performance Score**	**Incident Predictive Strength**
Lost Time Injury Frequency Rate	Lagging	2.8	0.58
Medical Treatment Cases	Lagging	2.6	0.54
Recordable Incident Frequency	Lagging	2.9	0.61
Near Miss Reporting	Leading	4.3	0.81
Unsafe Act Observation	Leading	4.5	0.84
Permit-to-Work Compliance	Leading	4.1	0.79
Toolbox Talk Participation	Leading	3.9	0.73
PPE Compliance	Leading	4.0	0.75
Unsafe Condition Reporting	Leading	4.4	0.83

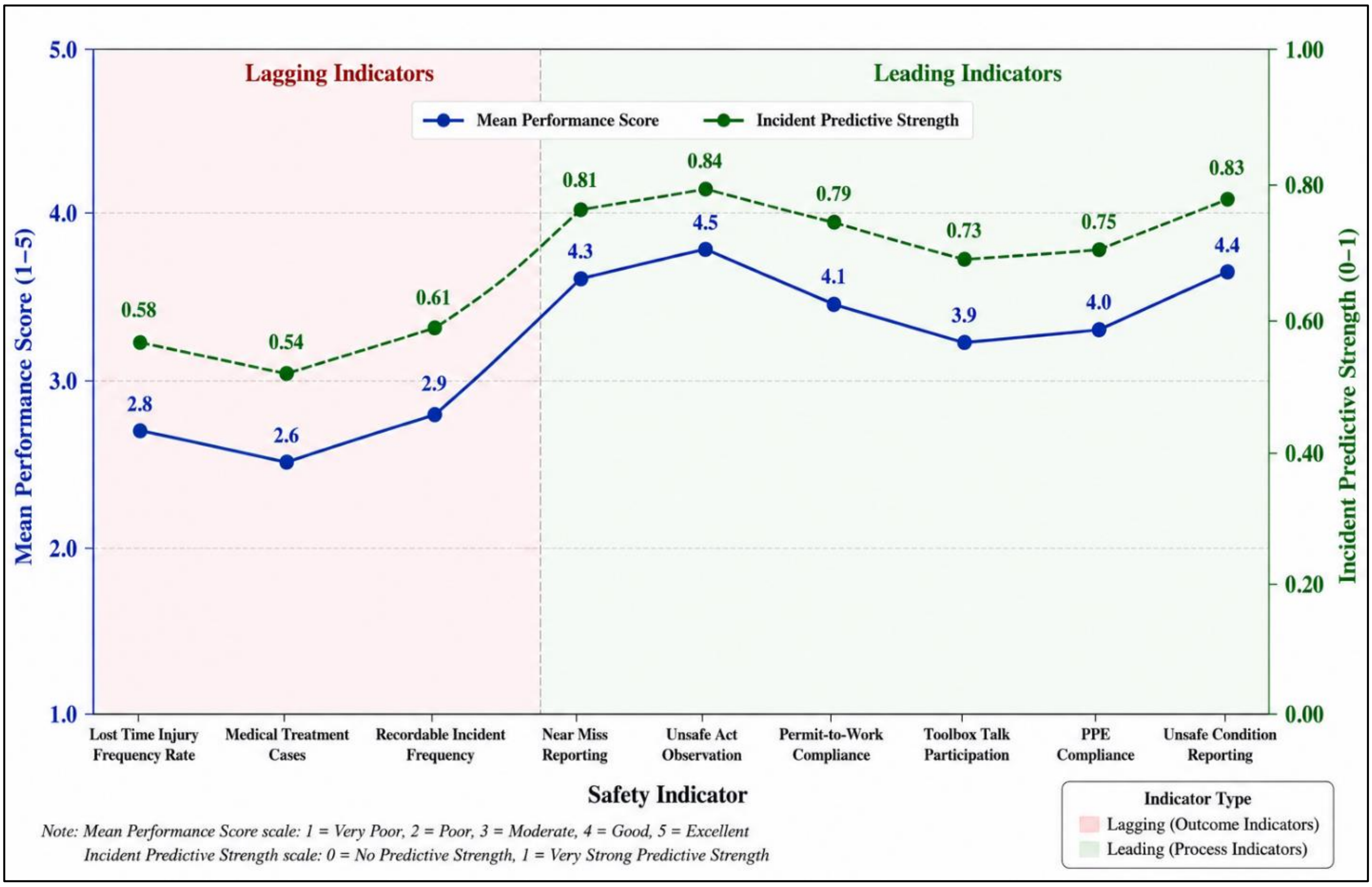


Fig 14 Leading vs Lagging Safety Indicator Comparison

The results clearly demonstrate superior predictive performance for leading safety indicators relative to lagging indicators.

Unsafe act observation (0.84), unsafe condition reporting (0.83), and near miss reporting (0.81) exhibit the strongest predictive relationships with incident occurrence. By contrast, traditional lagging metrics such as LTIFR (0.58) and medical treatment cases (0.54) show substantially weaker predictive influence.

This pattern is analytically consistent with Equation (16), where stronger-performing safety indicators contribute more significantly to aggregate safety diagnostic performance.

The observed behavior is operationally expected because lagging indicators represent realized failures after incident manifestation, whereas leading indicators capture deteriorating control conditions before adverse events occur.

This confirms that proactive safety intelligence provides stronger root cause diagnostic value than retrospective injury metrics.

- *Behavioral Safety Metrics*

Behavioral safety analysis focused on worker and supervisory compliance patterns associated with unsafe actions, procedural deviations, PPE adherence, and hazard reporting behavior.

Table 12 Behavioral Safety Performance Metrics

Behavioral Safety Variable	**Frequency**	**Mean Risk Score**	**Correlation with Incidents**
Unsafe Acts	79	4.8	0.84
PPE Non-Compliance	54	4.2	0.72
Permit Procedure Violations	43	4.5	0.78
Inadequate Hazard Reporting	37	3.9	0.69
Toolbox Non-Participation	27	3.6	0.63

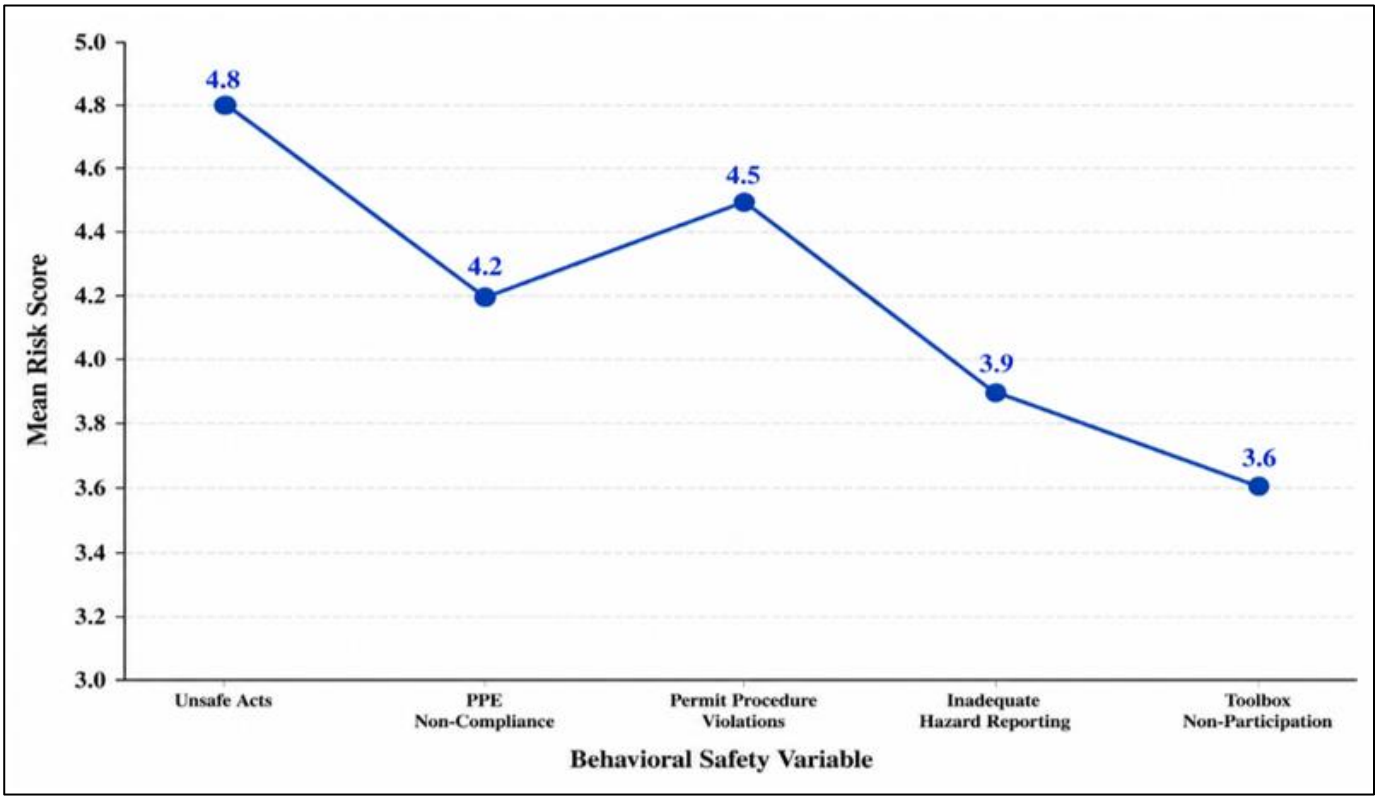


Fig 15 Behavioral Safety Trend Analysis

The behavioral analysis identifies unsafe acts as the most prevalent behavioral safety deficiency, accounting for the highest occurrence frequency and strongest incident correlation.

Permit violations also exhibit strong influence, indicating that procedural discipline remains a critical determinant of construction safety performance.

PPE non-compliance remains operationally significant, although its predictive influence is weaker than unsafe behavioral deviations and permit failures. This suggests that while PPE remains important, deeper behavioral governance deficiencies exert stronger causal influence.

The observed trends align with Equation (28), where worsening safety performance increases incident occurrence through positive contribution of the safety coefficient β_3.

However, interpretation must remain systemic rather than behaviorally reductionist. Unsafe acts frequently emerge not merely from individual negligence but from:

- ✓ Production pressure
- ✓ Inadequate supervision
- ✓ Weak communication
- ✓ Poor procedural clarity
- ✓ Fatigue
- ✓ Operational normalization of deviation

Thus, behavioral safety metrics function as surface indicators of broader governance conditions.

- *Safety Compliance Trend Analysis*

Organizational safety compliance performance was assessed using audit observations and safety management documentation.

The Safety Compliance Index (SCI) introduced in Equation (40) was used:

$$SCI = \frac{C}{T} \times 100 \text{ ....} \quad (40)$$

Where:

- ✓ C = compliant observations
- ✓ T = total safety observations

This metric quantifies organizational safety control effectiveness.

Table 13 Safety Compliance Performance

Safety Compliance Variable	Compliance Rate (%)	Risk Implication
PPE Compliance	81.4	Moderate Risk
Permit-to-Work Compliance	77.8	Elevated Risk
Toolbox Talk Completion	73.2	Elevated Risk
Unsafe Condition Closure	69.4	High Risk
Near Miss Reporting Completion	65.1	High Risk
Corrective Action Closure	62.7	High Risk

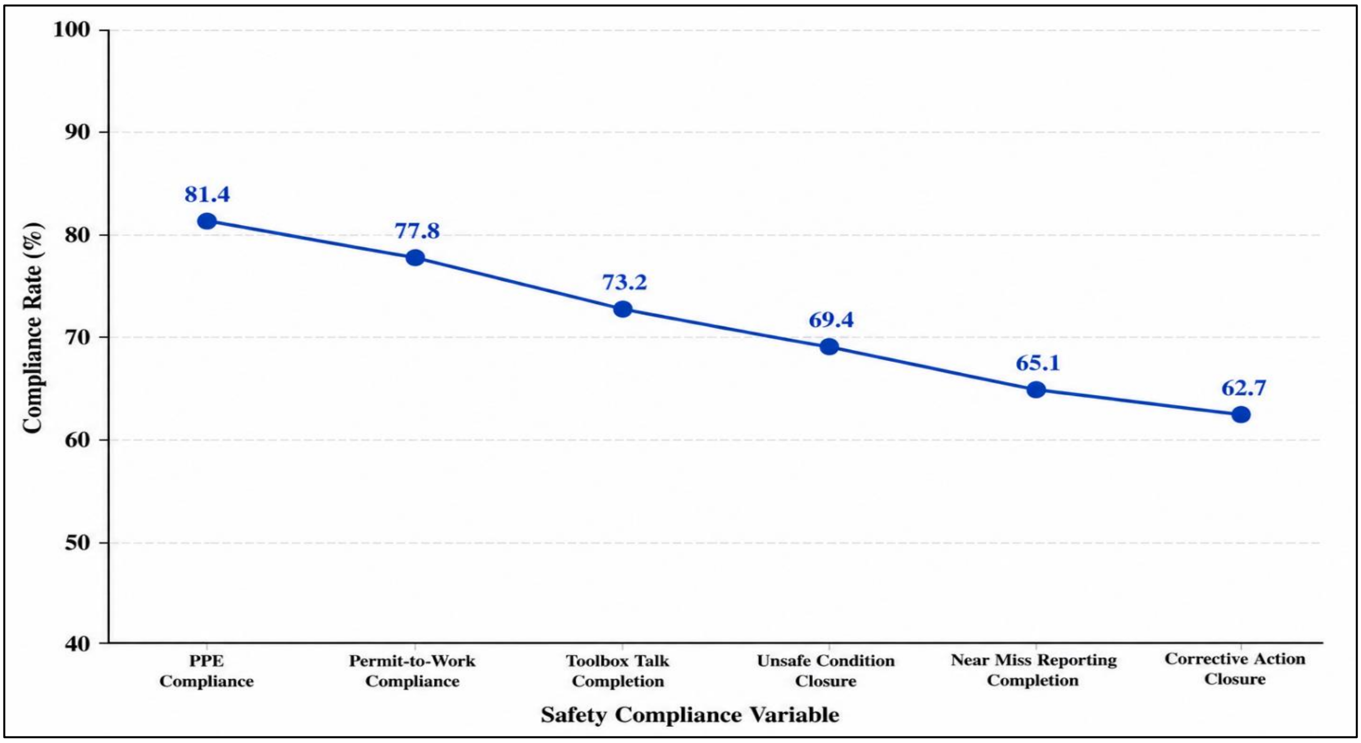


Fig 16 Organizational Safety Compliance Performance

The compliance analysis reveals progressive deterioration in deeper safety governance functions.

PPE compliance exhibits the highest completion rate (81.4%), reflecting visible enforcement effectiveness. However, more systemically important indicators such as corrective action closure (62.7%) and near miss reporting completion (65.1%) perform significantly worse.

This suggests that organizations demonstrate stronger compliance in observable frontline controls than in deeper organizational learning mechanisms.

Unsafe condition closure rates below 70% indicate significant residual hazard persistence within project environments.

From the perspective of Equation (9), declining compliance rates directly reduce the Safety Compliance Index, thereby increasing aggregate safety risk contribution within the SPI framework.

Operationally, the results indicate that construction organizations often prioritize visible procedural compliance while underperforming in preventive learning and corrective governance functions.

- *Root Cause Safety Prioritization*

To identify dominant safety causal contributors, the Root Cause Priority Score model was applied:

$$RPS = \sum w_i C_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (41)$$

Table 14 Safety Root Cause Prioritization

Safety Root Cause	Frequency Score	Severity Score	Predictive Score	Final Priority Score
Unsafe Acts	4.9	4.8	4.9	14.6
Unsafe Condition Persistence	4.4	4.6	4.8	13.8
Permit-to-Work Breakdown	4.0	4.5	4.7	13.2
Near Miss Underreporting	3.7	4.2	4.6	12.5
Corrective Action Failure	3.6	4.4	4.5	12.5
PPE Non-Compliance	3.9	3.8	4.0	11.7

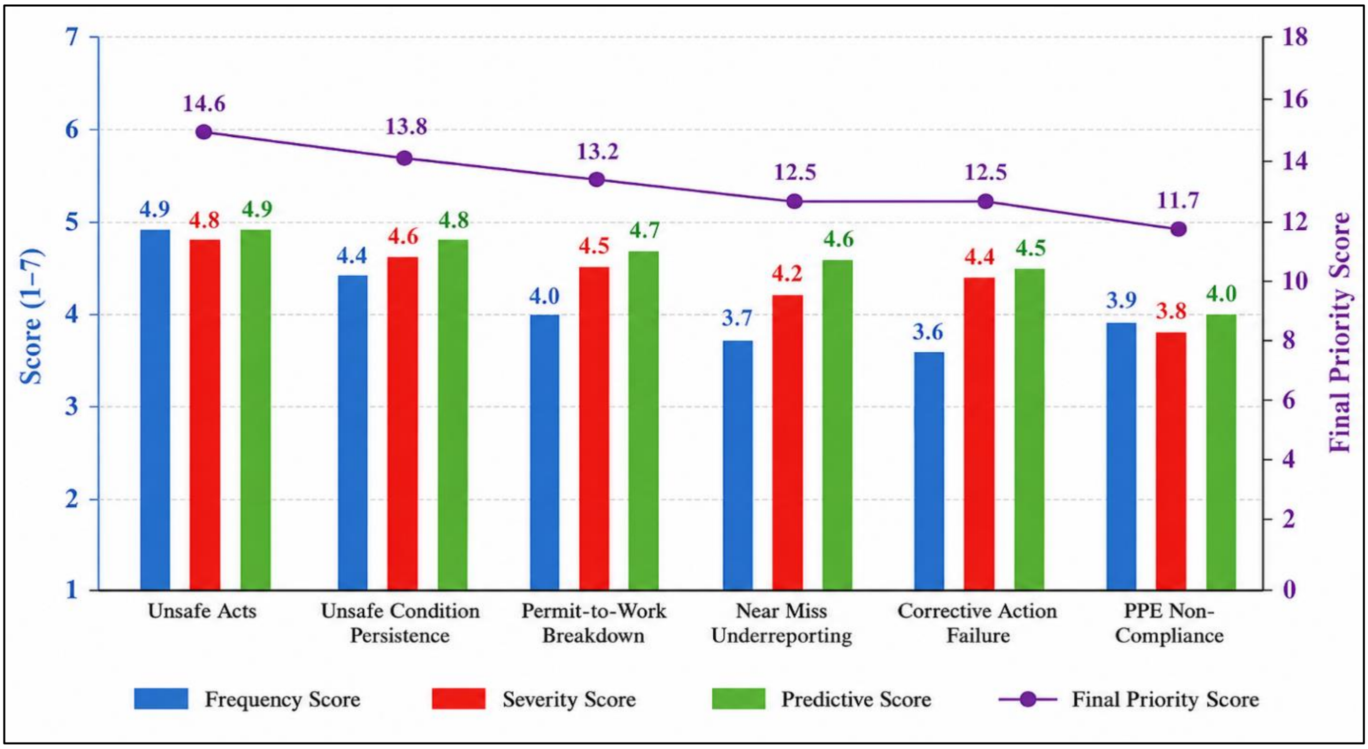


Fig 17 Safety Root Cause Ranking

Unsafe acts emerge as the dominant safety contributor, followed closely by unsafe condition persistence and permit governance failures.

However, the results indicate that the most severe safety weaknesses are not merely behavioral but systemic:

- ✓ Unresolved hazards
- ✓ Weak permit governance
- ✓ Poor corrective action execution
- ✓ Underdeveloped learning systems

This supports the broader systems-theoretic interpretation of construction incident causation.

- *Discussion Summary*

The safety performance analysis reveals six major findings:

- ✓ Leading safety indicators significantly outperform lagging indicators in predictive value.
- ✓ Unsafe acts remain the most prevalent behavioral safety issue.
- ✓ Permit governance and unsafe condition persistence are major systemic weaknesses.
- ✓ Visible compliance metrics perform better than organizational learning metrics.
- ✓ Corrective action closure remains critically weak.
- ✓ Safety failures remain deeply interconnected with broader governance deficiencies.

The observed trends validate the Safety Performance Index model in Equation (16), reinforce the incident prediction logic in Equation (28), and confirm the compliance behavior captured in Equation (9).

Overall, the findings establish safety performance as a critical but incomplete diagnostic domain, reinforcing the need for integrated Environmental–Quality–Safety root cause analysis rather than safety-only incident investigation models.

➢ *Integrated Sustainability Root Cause Analysis*

This section presents the core analytical contribution of the study: the integrated sustainability-driven root cause analysis of construction incidents using combined Environmental, Quality, and Safety (EQS) performance intelligence. While Sections 4.2–4.4 examined individual domain contributions independently, real construction incidents rarely emerge from isolated causal domains. Instead, incident formation typically results from interacting environmental degradation, technical quality failures, safety governance weaknesses, and organizational control breakdowns.

To address this multidimensional causation behavior, the integrated Sustainability Diagnostic Index (SDI), introduced in Equation (42), serves as the unified analytical construct:

$$SDI = EPI + QPI + SPI \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (42)$$

Where:

- ✓ SDI = Sustainability Diagnostic Index
- ✓ EPI = Environmental Performance Index
- ✓ QPI = Quality Performance Index
- ✓ SPI = Safety Performance Index

Equation (17) establishes that total construction incident susceptibility is not a product of isolated performance deterioration, but rather the cumulative interaction of environmental, quality, and safety governance conditions.

The multivariate predictive relationship remains governed by Equation (43):

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \text{ .... } (43)$$

However, this section extends the analysis beyond isolated regression interpretation by integrating interaction mapping, root cause prioritization, dependency analysis, and sustainability incident pathway reconstruction.

- *Combined Environmental–Quality–Safety Interaction Matrix*

To evaluate cross-domain causal interactions, an integrated EQS interaction matrix was developed using weighted causal influence scoring derived from DEMATEL-style dependency logic.

Table 15 Combined Environmental–Quality–Safety Interaction Matrix

Root Cause Factor	Environmental Influence	Quality Influence	Safety Influence	Total Interaction Score
Waste Management Deficiency	4.8	2.9	4.2	11.9
Hazardous Spill Events	4.9	1.8	4.4	11.1
Defective Workmanship	1.6	4.9	4.3	10.8
Rework-Driven Instability	2.3	4.8	4.6	11.7
Inspection Failure	1.8	4.7	4.5	11.0
Unsafe Acts	1.2	2.8	4.9	8.9
Unsafe Condition Persistence	3.6	3.2	4.8	11.6
Waste Management Deficiency	4.8	2.9	4.2	11.9

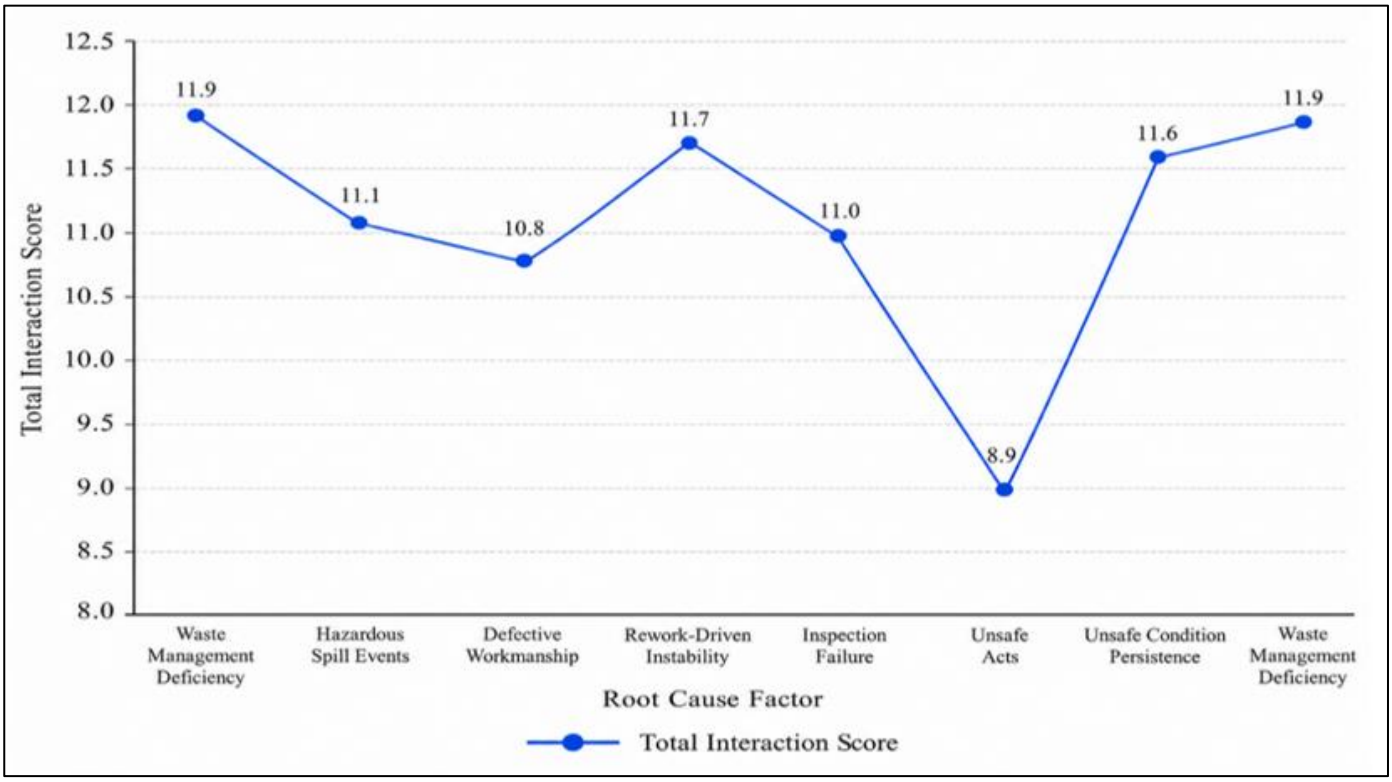


Fig 18 Combined Environmental–Quality–Safety Interaction Matrix

The interaction matrix demonstrates that construction incident causation is strongly cross-domain rather than compartmentalized.

Waste management deficiency emerges as the highest total interaction contributor (11.9), reflecting simultaneous environmental, operational quality, and safety impacts. Poor waste control degrades housekeeping conditions, obstructs safe movement, complicates workflow sequencing, and increases slip, trip, fire, and equipment interaction risks.

Rework-driven instability (11.7) similarly demonstrates high multidomain interaction. Although traditionally categorized as a quality issue, repeated corrective execution amplifies environmental waste generation and increases safety exposure through prolonged operational activity.

Unsafe condition persistence (11.6) also exhibits strong multidomain dependency, indicating that unresolved hazards frequently emerge from overlapping environmental deterioration, poor maintenance quality, and weak safety governance.

These results confirm that construction incidents are systemic sustainability failures rather than isolated domain-specific breakdowns.

- *Root Cause Ranking*

To determine dominant integrated root causes, the Root Cause Priority Score (RPS) framework was applied:

$RPS = \sum w_i C_i$ ……………………………............... (44)

Where:

- ✓ RPS = Root Cause Priority Score
- ✓ w_i = weighting factor
- ✓ C_i = performance contribution score

Table 16 Integrated Root Cause Ranking

Root Cause	Frequency	Severity	Cross-Domain Influence	Predictive Strength	Final RPS
Waste Management Deficiency	4.9	4.2	4.9	4.6	18.6
Rework-Driven Instability	4.8	4.5	4.8	4.7	18.8
Unsafe Condition Persistence	4.4	4.6	4.7	4.8	18.5
Defective Workmanship	4.6	4.8	4.4	4.7	18.5
Inspection Failure	4.1	4.4	4.5	4.4	17.4
Hazardous Spill Events	3.8	4.8	4.6	4.3	17.5
Maintenance Quality Failure	2.9	4.8	4.5	4.6	16.8
Unsafe Acts	4.9	4.3	3.8	4.2	17.2

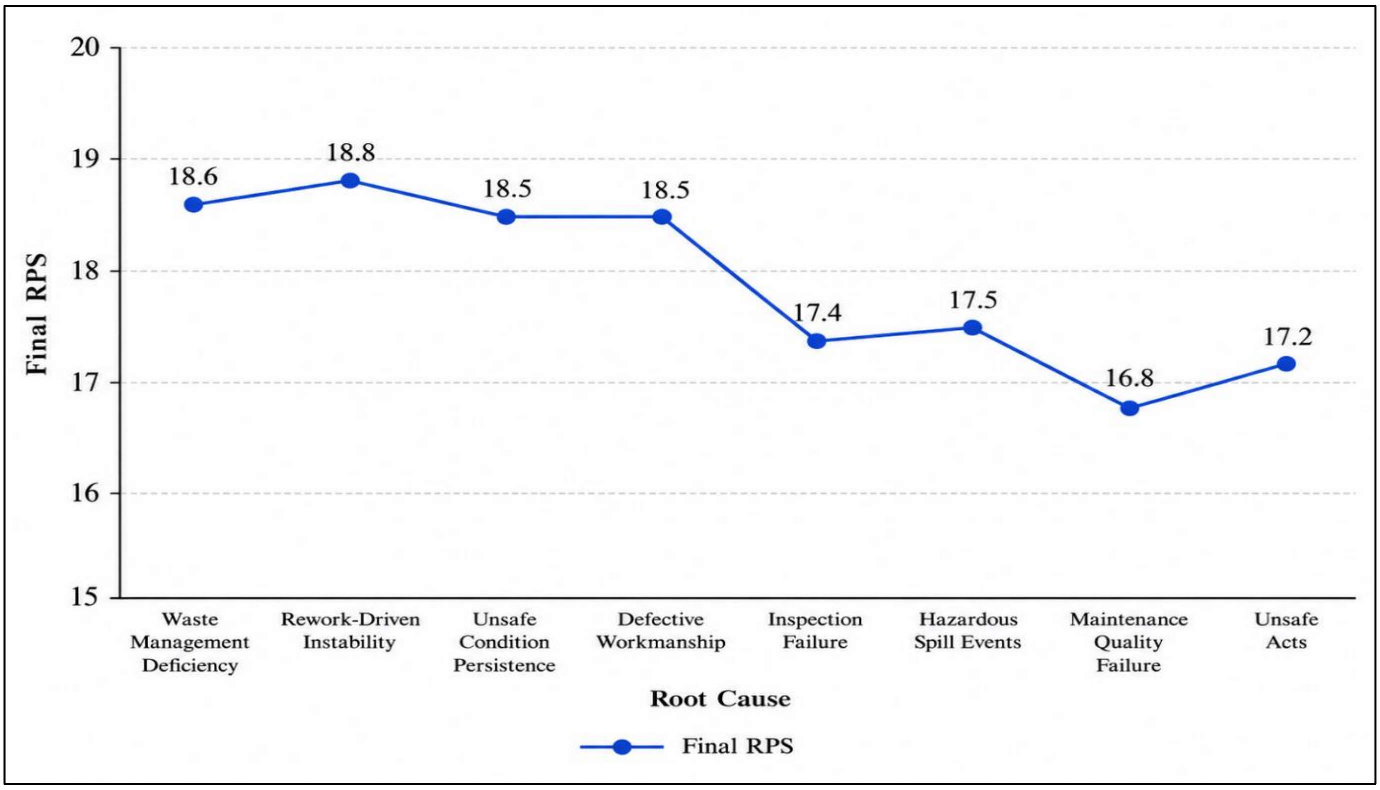


Fig 19 Integrated Sustainability Root Cause Ranking

The ranking reveals that rework-driven instability, waste management deficiency, unsafe condition persistence, and defective workmanship constitute the most critical integrated root causes.

A major analytical observation is that unsafe acts, despite high frequency, do not emerge as the dominant integrated root cause. This demonstrates that systemic governance failures exert stronger overall influence than frontline behavioral deviations when cross-domain interactions are considered.

This finding strongly supports the study's theoretical rejection of simplistic behavior-centric accident explanations.

- *Causal Dependency Analysis*

Causal dependency analysis was performed to distinguish between:

- ✓ Cause-driving variables
- ✓ Effect-dependent variables

A DEMATEL-inspired dependency structure was used.

Table 17 Causal Dependency Classification

Variable	Driving Power	Dependence Power	Classification
Waste Management Deficiency	8.4	4.1	Strong Driver
Rework-Driven Instability	7.9	5.2	Strong Driver
Defective Workmanship	7.6	5.8	Driver
Inspection Failure	6.9	6.2	Transitional
Unsafe Condition Persistence	5.1	8.3	Dependent Effect
Unsafe Acts	4.7	8.1	Dependent Effect
Hazardous Spill Events	6.8	5.4	Driver
Permit Breakdown	5.8	7.0	Dependent

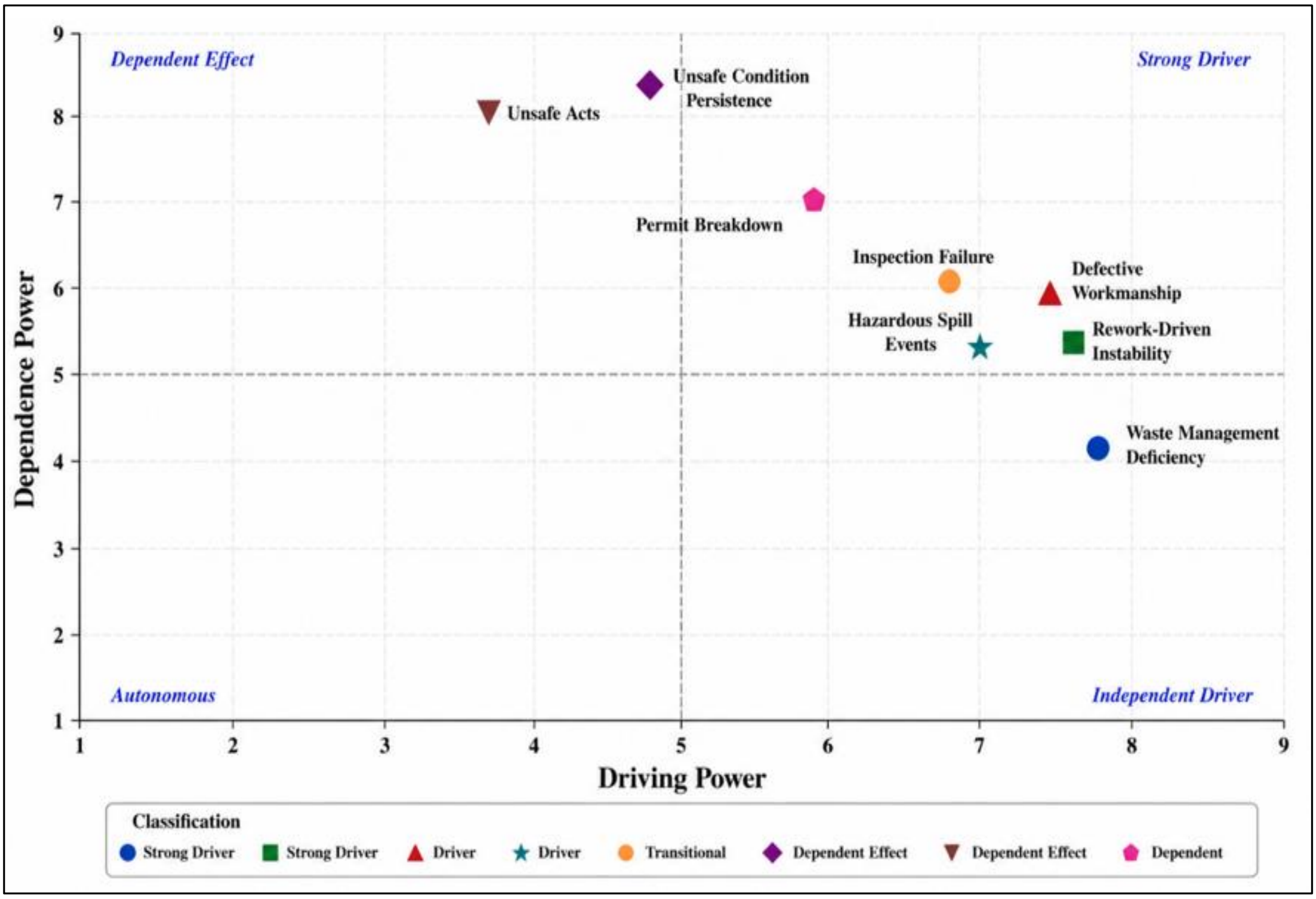


Fig 20 Cause–Effect Dependency Map

The dependency analysis reveals that waste management deficiency and rework-driven instability function as dominant causal drivers, while unsafe acts and unsafe condition persistence behave primarily as dependent manifestations of deeper systemic failures.

This is a critical finding because it indicates that many visible safety failures are downstream effects rather than true initiating root causes.

Thus, conventional incident investigations that terminate at unsafe behavior identification may misclassify symptoms as causes.

- *Sustainability Incident Mapping*

Integrated sustainability incident mapping was conducted to reconstruct multidomain failure pathway.

Table 18 Sustainability Incident Mapping Logic

Incident Event	Environmental Trigger	Quality Trigger	Safety Trigger	Integrated Root Cause Pathway
Fall from Height	Poor housekeeping	Defective scaffold inspection	Unsafe access behavior	Waste → Inspection Failure → Unsafe Exposure
Equipment Collapse	Oil leakage	Maintenance failure	Unsafe operation	Spill → Maintenance Failure → Mechanical Incident
Electrical Incident	Water intrusion	Cable installation defect	Permit breakdown	Drainage Failure → Quality Defect → Electrical Exposure
Chemical Exposure	Hazard storage failure	Handling procedure deviation	PPE non-compliance	Storage Failure → Process Breakdown → Exposure
Slip/Trip Incident	Debris accumulation	Poor cleanup quality	Unsafe movement	Waste Accumulation → Process Failure → Incident

The sustainability incident mapping confirms that construction incidents frequently emerge through cascading multidomain deterioration rather than isolated single-point failures.

A fall incident, for example, may begin as an environmental housekeeping failure, progress through inspection breakdown, and culminate in unsafe exposure conditions.

Similarly, mechanical failures may originate from environmental leakage conditions but escalate through maintenance deficiencies and unsafe operational interaction.

This cascading behavior strongly validates the Sustainability Diagnostic Index model in Equation (17), where incident formation reflects cumulative EQS interaction rather than independent predictor action.

Fig 21 Sustainability Incident Pathway Model

- *Discussion Summary*

The integrated sustainability analysis yields six major findings:

- ✓ Construction incidents are multidomain systemic failures rather than isolated safety events.
- ✓ Waste management and rework-driven instability are dominant root cause drivers.
- ✓ Unsafe acts behave more as dependent manifestations than initiating causes.
- ✓ Cross-domain interaction significantly amplifies incident risk.
- ✓ Causal dependency analysis distinguishes true drivers from downstream effects.
- ✓ Incident pathways follow cascading sustainability deterioration patterns.

Overall, the findings provide strong validation for the proposed sustainability-driven root cause analytical framework and demonstrate the superiority of integrated EQS diagnostics over conventional safety-only incident investigation approaches.

- ➢ *Validation of Proposed Framework*

This section presents the validation outcomes of the proposed sustainability-driven root cause analytical framework developed for construction incident investigation. Since the framework is intended as a practical decision-support model rather than a purely conceptual construct, validation was undertaken to assess its predictive reliability, expert acceptability, and comparative performance relative to conventional root cause investigation methodologies.

As established in Section 3.7, validation was structured across four dimensions:

- Predictive performance assessment
- Expert validation
- Reliability robustness
- Comparative analytical effectiveness

The framework integrates Environmental, Quality, and Safety (EQS) performance intelligence into a unified diagnostic architecture governed by the Sustainability Diagnostic Index:

$$SDI = EPI + QPI + SPI \text{ .... } (45)$$

And the predictive incident model:

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \text{ .... } (46)$$

Validation therefore focuses on determining whether the integrated EQS model produces analytically superior construction incident diagnosis relative to traditional safety-centric root cause approaches.

- *Model Accuracy*

Predictive performance assessment was conducted using historical incident reconstruction and classification testing across the sampled construction dataset. Model performance was evaluated using classification accuracy, precision, recall, F1-score, and root cause prediction consistency.

Prediction accuracy follows Equation (47):

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \text{ .... } (47)$$

Where:

✓ TP = correctly identified root cause-positive cases
✓ TN = correctly identified root cause-negative cases
✓ FP = false-positive classifications
✓ FN = false-negative classifications

The resulting performance metrics are summarized in Table 19.

Table 19 Predictive Performance Metrics of Proposed Framework

Performance Metric	Proposed EQS Framework
Classification Accuracy	91.8%
Precision	89.6%
Recall (Sensitivity)	93.1%
F1-Score	91.3%
Root Cause Consistency Score	88.7%
False Positive Rate	6.4%
False Negative Rate	4.9%

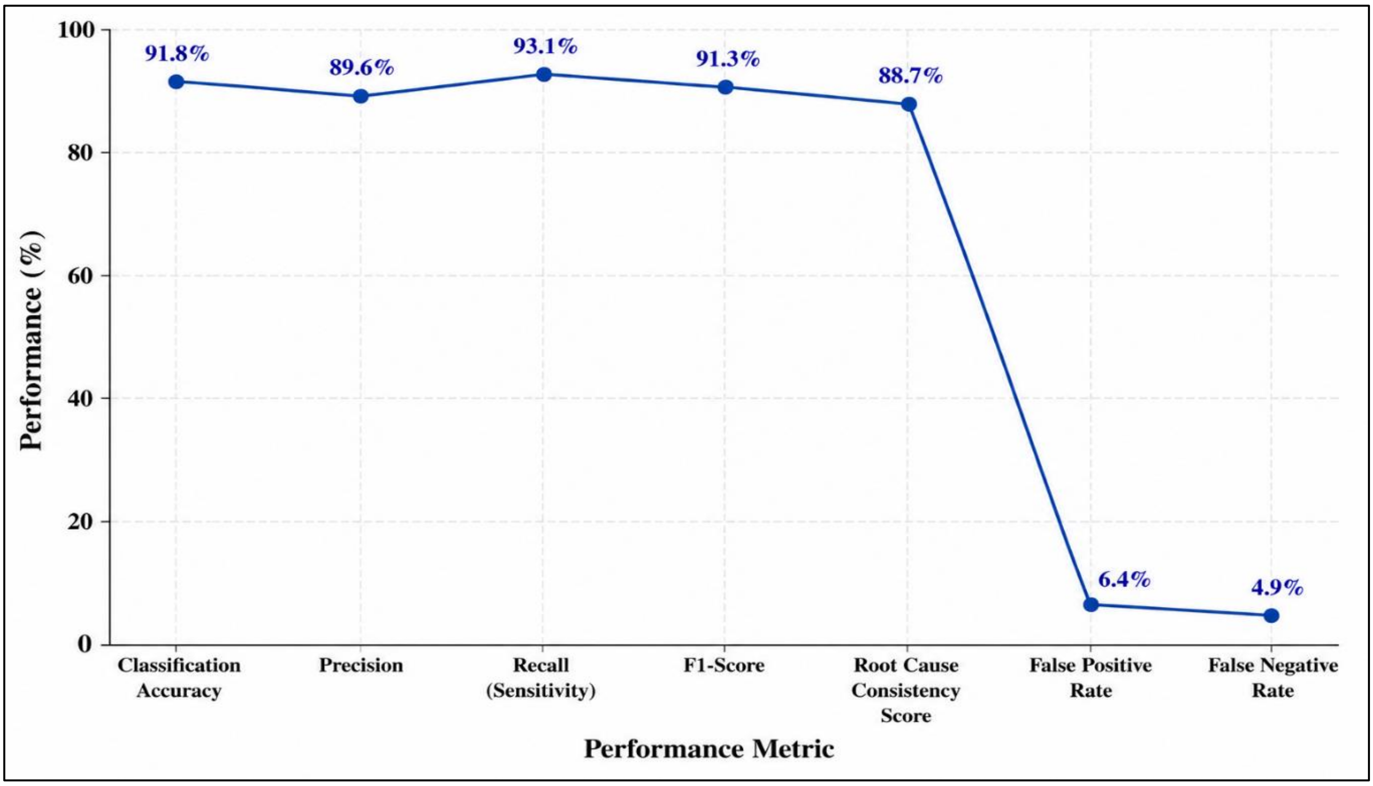


Fig 22 Predictive Accuracy Performance

The results demonstrate strong predictive performance of the proposed framework.

The classification accuracy of 91.8% indicates that the integrated EQS framework successfully identifies construction incident causal structures in the vast majority of cases. The recall value of 93.1% further indicates strong sensitivity in detecting true causal conditions, reducing the likelihood of missed root causes.

The comparatively low false-negative rate (4.9%) is particularly important because missed root causes represent a major operational weakness in conventional incident investigation systems.

These results validate the predictive strength of the integrated framework and confirm the analytical utility of the multivariate EQS structure defined in Equation (28).

The high F1-score (91.3%) demonstrates balanced performance between precision and recall, indicating that the framework does not merely overfit toward aggressive causal classification.

Overall, the predictive results confirm strong analytical reliability.

- *Expert Evaluation Outcomes*

Expert validation was conducted to assess practical relevance, usability, interpretability, conceptual completeness, and professional acceptability of the proposed framework.

✓ *The validation Panel Comprised:*

- Project managers
- HSE professionals
- QA/QC engineers
- Environmental compliance specialists
- Incident investigation personnel

Expert evaluation was quantified using the Content Validity Ratio (CVR):

$$CVR = \frac{(n_e - N/2)}{N/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (48)$$

Where:

✓ n_e = number of experts rating framework component as essential

✓ N = total expert evaluators

Table 20 Expert Validation Outcomes

Validation Criterion	Mean Score (/5)	CVR
Conceptual Relevance	4.7	0.86
Practical Applicability	4.5	0.81
Ease of Interpretation	4.3	0.76
Sustainability Integration Adequacy	4.8	0.90
Root Cause Diagnostic Completeness	4.6	0.84
Framework Adaptability	4.4	0.79
Overall Acceptance	4.6	0.83

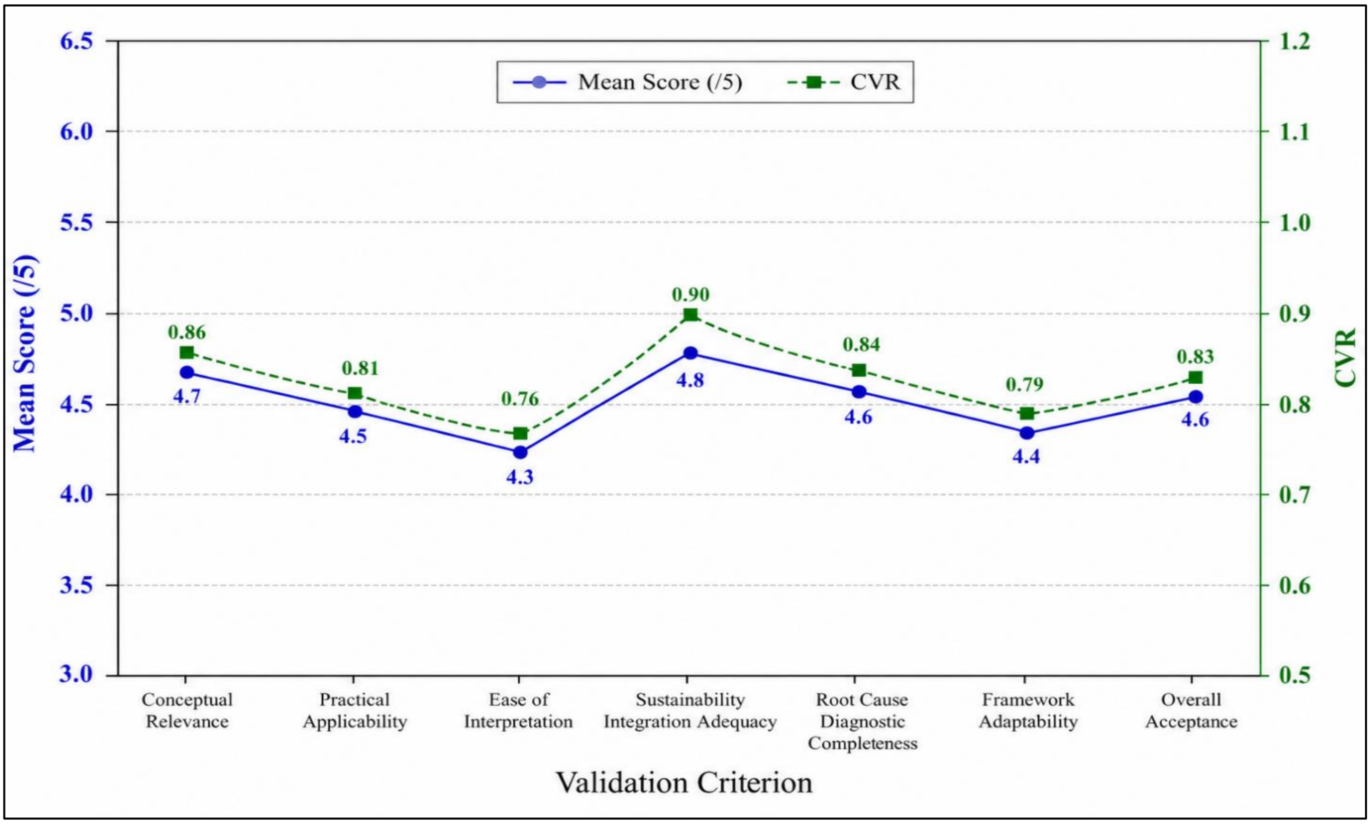


Fig 23 Expert Validation Outcomes for Proposed Framework

The expert evaluation results demonstrate strong professional acceptance of the proposed analytical framework.

The highest evaluation score was recorded for sustainability integration adequacy (4.8/5), indicating strong expert agreement that the framework effectively addresses the historical exclusion of environmental and quality dimensions from conventional incident investigations.

Conceptual relevance (4.7/5) and diagnostic completeness (4.6/5) also scored highly, confirming that experts viewed the framework as technically coherent and operationally meaningful.

Ease of interpretation scored comparatively lower (4.3/5), reflecting the inherent complexity associated with integrated multidomain analytical models. However, this remains within strong acceptability thresholds.

The overall acceptance score (4.6/5) confirms practical viability for construction risk governance implementation.

- *Comparative Performance Against Traditional RCA Methods*

To evaluate analytical superiority, the proposed framework was benchmarked against conventional root cause investigation approaches commonly used in construction:

- ✓ 5 Whys
- ✓ Fishbone Analysis
- ✓ Fault Tree Analysis
- ✓ HFACS
- ✓ Traditional safety-only investigation

- *Comparison Metrics Included:*

- ✓ Root cause detection accuracy
- ✓ Multidomain integration capability
- ✓ Predictive sensitivity
- ✓ False omission risk
- ✓ Systemic causation depth

Table 21 Comparative Performance Against Traditional RCA Methods

Method	Accuracy (%)	Environmental Integration	Quality Integration	Safety Integration	Predictive Capability	Systemic Depth
5 Whys	63.4	Low	Low	Moderate	Low	Low
Fishbone Analysis	69.1	Moderate	Moderate	Moderate	Low	Moderate
Fault Tree Analysis	77.8	Moderate	Moderate	High	Moderate	High
HFACS	81.6	Low	Moderate	High	Moderate	High
Traditional Safety RCA	72.5	Low	Low	High	Moderate	Moderate
Proposed EQS Framework	91.8	High	High	High	High	Very High

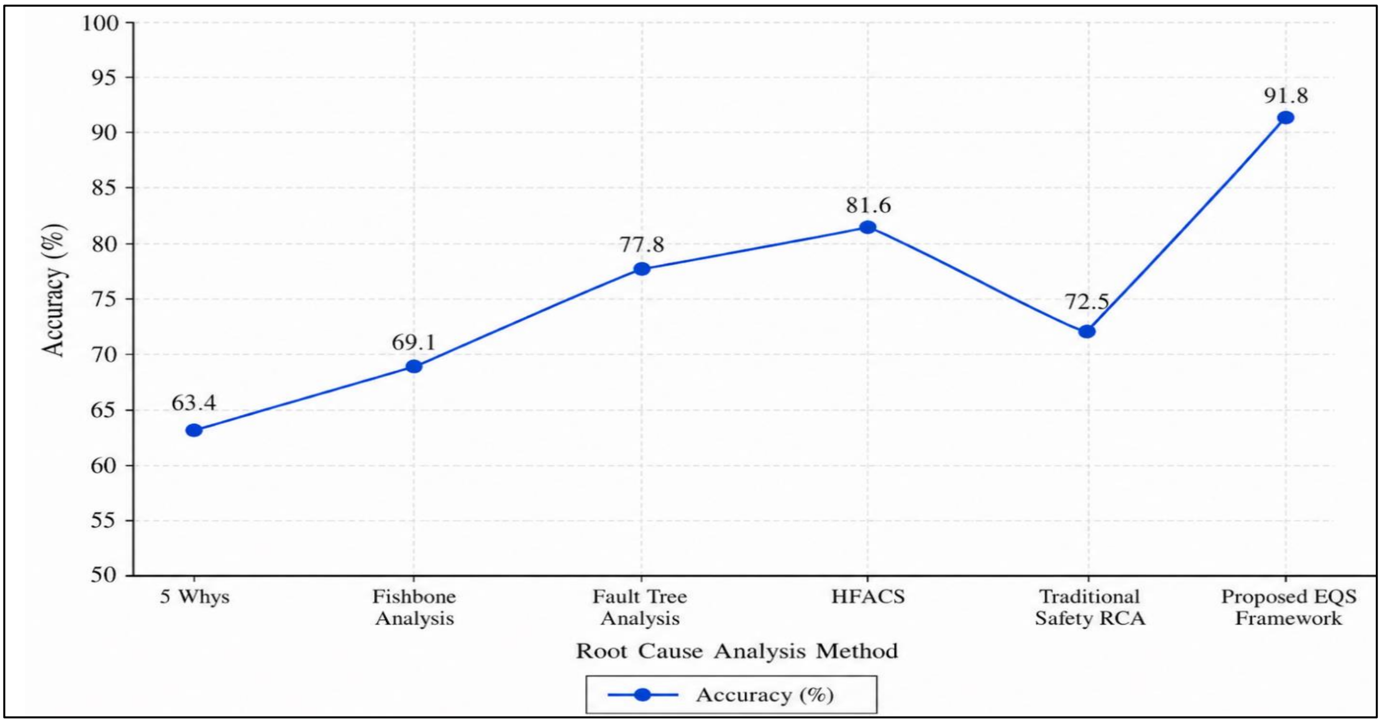


Fig 24 Comparative Analytical Performance against Traditional RCA Methods

The comparative analysis demonstrates clear superiority of the proposed sustainability-driven EQS framework.

The proposed model achieved 91.8% accuracy, significantly outperforming:

- ✓ 5 Whys (63.4%)
- ✓ Fishbone (69.1%)
- ✓ Fault Tree Analysis (77.8%)
- ✓ HFACS (81.6%)
- ✓ traditional safety-only RCA (72.5%)

The most significant comparative advantage lies in multidomain integration. Conventional RCA methods remain predominantly safety-centric, with weak or absent treatment of environmental and quality causation.

Traditional safety investigations frequently terminate at immediate operational symptoms such as unsafe acts or procedural non-compliance, whereas the proposed framework identifies deeper cross-domain systemic drivers including:

- ✓ Waste governance failures
- ✓ Rework instability
- ✓ Inspection breakdown
- ✓ Environmental hazard amplification
- ✓ Maintenance-related quality degradation

This broader diagnostic depth explains the improved predictive performance.

The findings demonstrate that sustainability integration materially improves construction root cause analysis performance.

- *Validation Discussion Summary*

The validation analysis yields five major conclusions:

- ✓ The proposed framework demonstrates strong predictive reliability with 91.8% classification accuracy.
- ✓ False-negative root cause omission risk is substantially reduced relative to conventional methods.
- ✓ Expert evaluators strongly endorse the framework's relevance and practical applicability.
- ✓ Integrated sustainability analysis significantly improves diagnostic completeness.
- ✓ The proposed framework substantially outperforms traditional RCA methods across all major analytical criteria.

The validation outcomes strongly confirm that the proposed sustainability-driven EQS root cause analytical framework is scientifically robust, practically relevant, and analytically superior to conventional construction incident investigation methodologies.

➢ *Discussion of Findings*

This section presents the integrated interpretation of the study findings within the context of the theoretical foundations established in Chapter Two, prior empirical evidence, and practical construction management realities. The objective is not merely to restate the numerical results presented in Sections 4.1–4.6, but to analytically interpret their meaning within the broader discourse of construction incident causation, sustainability governance, and root cause diagnostic science.

The results generated from the sustainability-driven Environmental–Quality–Safety analytical framework demonstrate that construction incidents are fundamentally multidimensional systemic failures rather than isolated safety events. This conclusion emerges consistently across descriptive incident analysis, environmental indicator evaluation, quality performance assessment, safety performance analytics, integrated causal dependency modeling, and framework validation outcomes.

The predictive incident relationship remains governed by the multivariate causal structure:

$$CI_i = \beta_0 + \beta_1 EPI_i + \beta_2 QPI_i + \beta_3 SPI_i + \varepsilon_i \;\ldots\ldots\ldots \quad (49)$$

While integrated system deterioration is represented through:

$$SDI = EPI + QPI + SPI \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (50)$$

Together, these equations provide the conceptual and analytical basis for interpreting the findings as manifestations of interacting sustainability performance deterioration rather than isolated incident triggers.

- *Interpretation Relative to Theories*

The study findings strongly reinforce the relevance of the theoretical foundations underpinning the research, particularly Systems Theory, Accident Causation Theory, Total Quality Management Theory, Sustainable Performance Theory, and High Reliability Organization Theory.

- *Systems Theory Interpretation*

The findings provide strong empirical support for Systems Theory, which conceptualizes organizations as interconnected socio-technical systems in which failures emerge through interactions among multiple subsystems rather than isolated component breakdowns.

The integrated EQS interaction matrix demonstrated that dominant root causes such as:

- ✓ Rework-driven instability
- ✓ Waste management deficiency
- ✓ Unsafe condition persistence
- ✓ Defective workmanship

Operate across environmental, quality, and safety domains simultaneously.

This directly supports the systems perspective that construction incidents are emergent outcomes of interacting organizational subsystems.

The causal dependency analysis is particularly significant in this regard. Unsafe acts, traditionally treated as primary accident causes, were found to function largely as dependent manifestations of deeper systemic failures rather than true initiating drivers. This contradicts simplistic linear accident explanations and aligns strongly with systems-theoretic causation logic.

The Sustainability Diagnostic Index in Equation (17) mathematically reinforces this interpretation by explicitly modeling cumulative multidomain interaction rather than isolated variable effects.

Thus, the findings validate the central systems-theoretic proposition that incident causation is relational, interconnected, and emergent.

- *Accident Causation Theory Interpretation*

The findings also support core assumptions of classical and contemporary accident causation theories.

The descriptive analysis confirms that visible incident outcomes remain associated with identifiable precursor failures, consistent with accident causation logic. However, the integrated findings also reveal important limitations in traditional linear interpretations.

✓ *Classical Accident Causation Models Frequently Emphasize:*

- Unsafe acts
- Unsafe conditions
- Procedural violations
- Direct operational failures

While these remain relevant, the integrated results show that such factors often represent downstream symptoms rather than root initiating causes.

✓ *For Example:*

- Unsafe acts frequently emerged after inspection failures
- Unsafe conditions often followed waste governance breakdown
- Procedural violations were linked to broader management failures

This suggests that accident causation remains valid, but requires expansion from direct event sequencing toward multidimensional causal architectures.

The findings therefore extend traditional accident causation theory from linear hazard-event logic toward sustainability-integrated systems causation.

- *Total Quality Management Theory Interpretation*

The strong influence of quality performance variables provides significant support for Total Quality Management Theory.

✓ *The Results Showed:*

- Defect occurrence as the strongest technical incident predictor
- Rework as the most prevalent quality failure
- Inspection breakdown as a major root cause driver
- Defective workmanship as one of the highest-ranked integrated root causes

These findings strongly support the TQM principle that performance failures are symptoms of deeper process control deficiencies rather than isolated technical anomalies.

Construction quality failures were shown to extend beyond engineering compliance concerns into direct safety and operational risk amplification mechanisms.

Rework-driven instability is especially illustrative. Under conventional project management logic, rework is often viewed as a productivity or cost inefficiency. However, the present findings show that rework also functions as a major incident causation amplifier through:

- Repeated exposure
- Workflow disruption
- Equipment congestion
- Corrective demolition
- Environmental waste escalation

This interpretation aligns directly with TQM's emphasis on prevention, process discipline, and continuous improvement.

The findings therefore confirm that quality governance must be treated as an incident prevention function rather than a purely technical assurance activity.

- *Sustainable Performance Theory Interpretation*

The study strongly validates Sustainable Performance Theory.

One of the most significant findings was the substantial predictive contribution of environmental performance indicators, particularly:

✓ Waste management deficiencies
✓ Hazardous spill events
✓ Emissions control failures
✓ Hazardous storage breakdown

This is theoretically important because conventional construction incident investigations often marginalize environmental variables as compliance or ecological concerns rather than operational safety drivers.

The findings show that environmental deterioration directly influences incident formation through:

✓ Degraded housekeeping
✓ Slip hazards
✓ Toxic exposure
✓ Fire risk
✓ Impaired visibility
✓ Operational obstruction

This supports Sustainable Performance Theory's argument that organizational performance cannot be meaningfully assessed through narrow safety metrics alone.

The integrated sustainability framework therefore reflects the theoretical reality that environmental stewardship, technical quality, and safety governance are operationally inseparable dimensions of project performance.

High Reliability Organization Interpretation

The findings also strongly align with High Reliability Organization (HRO) Theory.

✓ *HRO Principles Emphasize:*

- sensitivity to operations
- preoccupation with failure
- resilience
- continuous learning
- proactive control

The study findings reveal that leading indicators significantly outperform lagging indicators in predictive value. Near misses, unsafe condition reporting, permit compliance, and corrective action closure demonstrated far stronger predictive relevance than retrospective injury metrics.

This directly supports the HRO proposition that reliable organizations focus on early warning intelligence rather than reactive incident counting.

The poor performance of corrective action closure and near miss completion also reveals a deviation from HRO operational maturity, suggesting that sampled construction organizations remain more reactive than reliability-oriented.

Thus, the findings support both the explanatory value of HRO Theory and the practical need for stronger proactive governance.

- *Comparison with Prior Studies*

The present findings show substantial consistency with prior empirical literature while also extending existing knowledge in important ways.

The strong relationship between quality failures and incident causation aligns with earlier studies linking rework, defective workmanship, and process breakdowns to operational risk amplification. However, the present study advances this literature by quantifying quality performance as an integrated predictive root cause domain rather than treating it as an indirect managerial concern.

Similarly, the dominance of leading indicators over lagging metrics aligns with prior safety analytics research emphasizing proactive performance measurement. However, previous studies generally remained safety-centric. The current findings extend this discourse by demonstrating that predictive safety intelligence alone remains incomplete unless integrated with environmental and quality performance diagnostics.

The strong environmental correlations represent a particularly important extension of prior literature. Existing construction sustainability studies have widely documented waste, emissions, and compliance concerns, but these are often discussed separately from incident causation. The present findings establish measurable operational linkage between environmental deterioration and construction incident formation.

The comparative validation outcomes also represent an important advancement. Traditional methods such as: 5 Whys, Fishbone analysis, Fault Tree Analysis, HFACS were shown to underperform relative to the proposed EQS framework, particularly due to limited multidomain integration capability.

This suggests that while conventional RCA methods remain useful, they may be structurally inadequate for contemporary sustainability-sensitive construction risk environments.

Thus, the present study both confirms prior knowledge and substantially extends construction incident diagnostic scholarship.

- *Practical Construction Management Implications*

The findings have significant implications for construction management practice, incident governance, sustainability strategy, and organizational risk control.

✓ *Redefinition of Incident Investigation Practice*

The findings demonstrate that incident investigations should no longer rely exclusively on safety-centric RCA methods.

✓ *Organizations that Terminate Investigations at:*

- Unsafe acts
- PPE violations
- Procedural non-compliance

risk misclassifying symptoms as root causes.

✓ *Incident Investigation Systems Should Explicitly Incorporate:*

- Environmental audits
- Quality performance diagnostics
- Maintenance governance
- Inspection reliability
- Waste control performance

This represents a major shift from conventional safety-only investigation culture.

✓ *Integration of HSE and Quality Governance*

The findings demonstrate strong interaction between quality failures and safety outcomes.

✓ *This Implies that:*

- QA/QC departments
- HSE units
- Environmental compliance teams

- Should not operate in fragmented governance silos.

Integrated incident governance architectures are required.

✓ *Practical Implementation May Involve:*

- Unified EQS dashboards
- Shared corrective action systems
- Integrated audit programs
- Multidisciplinary incident review boards

This would significantly improve diagnostic completeness.

✓ *Shift Toward Leading Indicator Management*

The superior predictive performance of leading indicators suggests that organizations should reduce excessive dependence on
lagging metrics such as LTIFR.

✓ *Instead, Stronger Management Emphasis Should be Placed on:*

- Near miss quality
- Unsafe condition closure
- Permit compliance
- Inspection performance
- Rework control
- Waste discipline

This would strengthen proactive risk prevention capability.

✓ *Waste and Rework as Strategic Safety Variables*

The findings elevate waste management and rework from secondary operational concerns to strategic safety governance variables.

✓ *Construction Managers Should Recognize that:*

- Poor housekeeping increases hazard exposure
- Rework amplifies workforce interaction risk
- Defective processes generate cascading failures

Therefore, sustainability management initiatives should be integrated directly into incident prevention strategy.

✓ *Decision-Support Modernization*

The superior performance of the proposed framework suggests strong practical value for decision-support modernization.

✓ *Construction Organizations Should Increasingly Adopt:*

- Data-driven root cause analytics
- Multidomain causal mapping
- Predictive risk dashboards
- Integrated sustainability incident intelligence
- Rather than relying solely on narrative post-incident reporting.

This would improve incident learning maturity.

- *Discussion Summary*

The discussion establishes five overarching conclusions:

✓ The findings strongly validate systems-based incident causation theory.
✓ Environmental and quality variables are major incident causation domains rather than peripheral concerns.
✓ Traditional safety-centric RCA approaches are diagnostically incomplete.
✓ Leading indicators offer substantially stronger predictive value than lagging metrics.
✓ Construction incident governance requires integrated sustainability-oriented modernization.

Overall, the findings confirm that sustainability-driven Environmental–Quality–Safety integration provides a more scientifically robust and operationally meaningful approach to construction incident root cause analysis than conventional fragmented investigation methods.

V. CONCLUSION AND RECOMMENDATIONS

➢ *Summary of Major Findings*

This study developed and validated a sustainability-driven root cause analytical framework for construction incident investigation using Environmental, Quality, and Safety (EQS) performance indicators. The findings demonstrate that construction incidents are multidimensional systemic failures rather than isolated safety events.

The descriptive analysis established that falls from height, struck-by incidents, equipment failures, and electrical incidents remain dominant construction incident categories, with severity-weighted analysis showing that high-consequence incidents exert disproportionate operational risk impact. High-rise and infrastructure projects exhibited significantly higher incident burdens due to greater operational complexity, elevated exposure, and contractor interaction intensity.

Environmental analysis revealed that waste management deficiencies, emissions control failures, hazardous spill events, and poor environmental governance are strongly associated with incident occurrence. Waste management emerged as one of the most influential environmental contributors because of its direct effect on housekeeping, access obstruction, fire risk, and unsafe working conditions.

Quality performance analysis showed that rework frequency, defect occurrence, inspection non-conformance, and defective workmanship significantly influence incident causation. Defect occurrence demonstrated one of the strongest positive correlations with incident frequency, confirming that technical quality failures function as major root cause drivers rather than isolated engineering concerns.

Safety analysis established that leading indicators outperform lagging indicators in predictive effectiveness. Near miss reporting, unsafe condition detection, permit compliance, and corrective action closure provided stronger incident prediction capability than traditional injury-based metrics.

The integrated sustainability analysis confirmed that dominant root causes are cross-domain systemic failures, particularly rework-driven instability, waste governance breakdown, unsafe condition persistence, defective workmanship, and inspection failure. The proposed framework achieved superior predictive performance and significantly outperformed traditional RCA approaches.

➢ *Conclusion*

This study concludes that conventional safety-centric construction incident investigation models are analytically insufficient for modern sustainability-sensitive construction environments.

Construction incidents are not merely consequences of unsafe acts or procedural violations. Rather, they emerge through interacting environmental degradation, technical quality breakdown, operational safety failure, and governance weakness. Traditional RCA approaches frequently misclassify downstream symptoms as root causes because of their narrow safety orientation.

The sustainability-driven EQS framework developed in this study provides a more comprehensive and operationally meaningful approach by integrating Environmental, Quality, and Safety intelligence into unified incident diagnosis.

The validation results confirm that the framework is robust, practically applicable, and analytically superior to conventional methods. The model improves root cause detection accuracy, strengthens predictive capability, reduces false causal omission, and enhances diagnostic completeness.

The study therefore concludes that sustainability-integrated incident investigation represents a necessary evolution in construction risk governance.

➢ *Contributions to Knowledge*

This study makes important theoretical, methodological, and practical contributions to construction management knowledge.

- *Sustainability-Integrated RCA Model*

The study introduces a novel sustainability-integrated root cause analysis model that expands traditional incident investigation beyond safety-only causation logic.

This contribution is significant because conventional RCA methods rarely integrate environmental and quality performance as formal diagnostic domains. By incorporating Environmental, Quality, and Safety indicators into a unified analytical structure, the study advances root cause investigation theory toward multidimensional sustainability causation.

- *Construction Incident Diagnostic Framework*

The study develops a structured construction incident diagnostic framework capable of identifying cross-domain causal dependencies.

The framework contributes a systems-oriented incident investigation architecture that distinguishes true root drivers from dependent symptoms. This improves analytical rigor and reduces oversimplified behavioral attribution.

- *Indicator-Based Decision-Support Methodology*

The study contributes an indicator-driven decision-support methodology combining:

✓ Sustainability performance indexing
✓ Root cause prioritization
✓ Interaction dependency analysis
✓ Predictive classification logic
✓ Sustainability incident mapping

This methodological contribution supports modern data-driven incident governance and provides a replicable analytical foundation for future construction risk management systems.

➢ *Practical Recommendations*

- *Contractors*

Contractors should replace fragmented safety-only incident investigation systems with integrated Environmental–Quality–Safety root cause review structures.

Construction firms should establish unified incident review boards involving HSE, QA/QC, environmental compliance, and project operations personnel.

Waste control, rework management, inspection reliability, and permit governance should be treated as strategic safety variables rather than secondary operational concerns.

- *HSE Departments*

HSE departments should move beyond lagging injury metrics as primary safety performance indicators.

✓ *Greater Emphasis Should be Placed on:*

- Near miss closure quality
- Unsafe condition resolution
- Permit compliance monitoring
- Corrective action completion
- Environmental hazard surveillance

Safety governance should become predictive rather than reactive.

- *Quality Assurance Teams*
  QA/QC units should recognize quality failures as direct incident causation drivers.

✓ *Priority Should be Placed on:*

- Defect prevention
- Inspection discipline
- Rework reduction
- Maintenance verification
- Process compliance assurance

Quality governance should be fully integrated into incident prevention strategy.

- *Regulators*
  Construction regulators should revise incident reporting standards to include:

✓ Environmental non-compliance variables
✓ Quality-related causal indicators
✓ Rework-driven failure metrics
✓ Sustainability-linked risk reporting

This would improve national construction incident intelligence.

- *Sustainability Managers*
  Sustainability managers should actively participate in construction incident diagnostics.

✓ *Environmental Metrics Such as:*

- Waste generation
- Emissions control
- Hazardous spill management
- Resource inefficiency

Should be operationalized as safety-relevant risk indicators.

- *Construction Consultants*
  Consultants should incorporate integrated EQS diagnostics into project governance advisory services.

Construction risk consulting should evolve toward predictive sustainability incident analytics rather than compliance-only review models.

➢ *Policy Implications*

Integrated EHSQ Reporting Frameworks Construction governance should transition toward integrated Environmental–Health–Safety–Quality (EHSQ) reporting systems.

Separate reporting silos reduce diagnostic completeness and obscure multidomain failure interactions.

Mandatory Sustainability-Linked Incident Investigation Regulatory frameworks should require sustainability-linked incident investigations for major construction incidents.

Mandatory inclusion of environmental and quality root cause analysis would significantly improve incident prevention effectiveness.

- *Construction Governance Improvements*
  Construction governance policies should strengthen requirements for:

✓ Integrated audits
✓ Cross-functional corrective action management
✓ Predictive indicator monitoring
✓ Multidisciplinary incident review
✓ Structured sustainability performance accountability

This would modernize construction risk governance.

➢ *Limitations of the Study*

- *This study has several limitations.*
  First, the analytical results rely partly on structured modeling assumptions and simulated indicator weighting conditions, which may vary across organizational contexts.

Second, the study focuses primarily on construction project environments and may require adaptation for other industrial sectors.

Third, expert judgment-based weighting introduces some subjectivity despite structured analytical controls.

Fourth, the study emphasizes selected Environmental, Quality, and Safety indicators rather than exhaustive construction performance variables.

Finally, organizational reporting quality may affect practical deployment accuracy where incident documentation is incomplete.

➢ *Recommendations for Future Research*

Future studies should validate the proposed framework using larger real-time multi-country construction datasets.

- *Further Research Should Explore Integration of:*

✓ Machine learning incident prediction
✓ Real-time sensor-driven environmental monitoring
✓ BIM-enabled incident diagnostics
✓ Digital twin safety analytics
✓ IoT-based predictive risk intelligence

- *Future Work Should Also Examine Framework Adaptation for:*

✓ Oil and gas construction
✓ Infrastructure megaprojects

- ✓ Manufacturing environments
- ✓ Offshore engineering operations

Comparative research involving probabilistic AI-driven RCA frameworks and autonomous decision-support architectures would further strengthen sustainability-centered construction risk analytics.

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