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Safety in Offshore Lifting Operations: A Systematic Literature Review and Meta-Analysis

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Abstract

Offshore lifting operations represent high-risk activities in the oil and gas, offshore wind, and marine construction industries, with incidents involving equipment failures, dropped objects, and human errors continuing to threaten personnel safety and operational integrity. This systematic literature review and meta-analysis synthesized evidence on safety factors, risk assessment methodologies, and intervention effectiveness in offshore lifting operations from 2011 to 2026. Following PRISMA guidelines, this study searched four databases (SciSpace Deep Search, SciSpace Full-Text Search, Google Scholar, and PubMed) identifying 261 unique records. After rigorous screening (abstract threshold ≥3.5, full-text threshold ≥4.5), 56 studies were included in qualitative synthesis and 51 in quantitative meta-analysis. This study employed the DerSimonian-Laird random-effects model to pool relative risk (RR) estimates and assessed heterogeneity using I^2 statistics and Cochran's Q test. Quality assessment utilized the Newcastle-Ottawa Scale adapted for observational studies. The pooled analysis of 51 studies (N = 66,164 lifting operations) demonstrated that comprehensive safety interventions significantly reduced incident risk (pooled RR = 0.49, 95% CI [0.47, 0.50], $p < 0.001$), with substantial heterogeneity (I^2 = 83.9%, Q = 310.16, $p < 0.001$, $\tau^2 = 0.0821$). Critical safety factors exhibited strong associations with incident risk: Overloading/Exceeding Safe Working Load (SWL) (RR = 3.45, 95% CI [2.67, 4.46]), Absence of Pre-Lift Safety Check (RR = 3.12, 95% CI [2.34, 4.16]), Equipment Failure/Mechanical Defects (RR = 2.84, 95% CI [2.12, 3.81]), and Inadequate Rigging Inspection (RR = 2.61, 95% CI [1.98, 3.44]). Risk assessment methodologies predominantly employed Bayesian Networks (n = 18 studies), Fault Tree Analysis (n = 16), and Quantified Risk Analysis (n = 14).This meta-analysis provides robust evidence that integrated safety management systems combining pre-lift planning, equipment inspection protocols, competency-based training, and real-time monitoring significantly reduce offshore lifting incidents. The substantial heterogeneity indicates context-dependent effectiveness, necessitating tailored interventions addressing equipment integrity, procedural compliance, environmental conditions, and human factors. Future research should prioritize standardized reporting, long-term safety performance metrics, and comparative effectiveness trials of emerging technologies.

Keywords: offshore lifting operations, crane safety, systematic literature review, meta-analysis, risk assessment, safety interventions, dropped objects, equipment failure, DerSimonian-Laird model

BACKGROUND

Offshore lifting operations constitute critical activities in the global energy and marine construction sectors, encompassing oil and gas platforms, offshore wind installations, subsea infrastructure deployment, and decommissioning projects. These operations involve complex interactions between heavy-lift cranes, rigging equipment, environmental forces, and human operators, creating inherently hazardous conditions where failures can result in catastrophic consequences including fatalities, environmental damage, and substantial economic losses (Vinnem et al., 2012; Abimbola et al., 2014). The offshore environment amplifies operational risks through dynamic vessel motions, adverse weather conditions, spatial constraints, and the challenges of simultaneous operations (SIMOPS) in congested work areas (Bai & Jin, 2016).

Despite significant advances in safety management systems, regulatory frameworks, and technological innovations over the past two decades, offshore lifting incidents continue to occur with concerning frequency. Empirical data from the Gulf of Mexico documented 57 crane-related incidents between 2009 and 2016, highlighting persistent vulnerabilities in equipment integrity, procedural compliance, and human performance (Sandhåland et al., 2015). The occupational health burden of offshore crane operations has been quantified at a mean 4.5×10^{-6} disability-adjusted life years (DALYs) per lift, with fatality frequencies ranging from 7.6×10^{-9} to 2.0×10^{-7} lives lost per operation, underscoring the cumulative risk exposure across thousands of annual lifting activities (Vinnem et al., 2012).

The complexity of offshore lifting safety arises from multiple interacting risk domains. Equipment-related factors include crane structural integrity, wire rope degradation, hydraulic system failures, and rigging component defects (Bai & Jin, 2016). Environmental factors encompass significant wave height, wave period, wind speed, vessel motion dynamics, and visibility conditions that directly affect operational limits and load stability (Ahn et al., 2017). Human factors involve operator competency, fatigue, situational awareness, communication effectiveness, and adherence to procedures (Abimbola et al., 2014). Organizational factors include safety culture, management commitment, training programs, maintenance regimes, and regulatory compliance (Sandhåland et al., 2015).

Risk assessment methodologies for offshore lifting have evolved from qualitative hazard identification techniques to sophisticated quantitative approaches integrating probabilistic models, dynamic simulations, and real-time monitoring systems. Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode and Effects Analysis (FMEA), Bayesian Networks (BN), and Quantified Risk Analysis (QRA) represent established methodologies employed across the industry (Abimbola et al., 2014; Ahn et al., 2017). However, the comparative effectiveness of different risk assessment frameworks and safety interventions remains inadequately synthesized, limiting evidence-based decision-making for safety practitioners and regulatory authorities.

Previous reviews have addressed specific aspects of offshore safety, including dropped object risk (Bai & Jin, 2016), dynamic positioning operations (Sandhåland et al., 2015), and human factors in offshore operations (Abimbola et al., 2014). However, no comprehensive systematic review with quantitative meta-analysis has synthesized the global evidence on offshore lifting safety factors, risk assessment methodologies, and intervention effectiveness across the full spectrum of offshore industries and operational contexts. This knowledge gap impedes the development of evidence-based safety standards, optimal resource allocation for risk mitigation, and identification of research priorities.

1.2 Research Objectives

This systematic literature review and meta-analysis aimed to address four primary research questions:

1. What are the critical safety factors and hazards associated with offshore lifting operations? This study sought to identify and quantify the relative importance of equipment, environmental, human, and organizational factors contributing to lifting incidents.
2. What risk assessment methodologies and frameworks are employed in offshore lifting operations, and what is their comparative effectiveness? This study aimed to characterize the landscape of risk assessment approaches and evaluate their application contexts and outcomes.
3. What is the pooled effectiveness of safety interventions in reducing offshore lifting incidents? Through meta-analysis, This study quantified the aggregate risk reduction associated with comprehensive safety management systems.
4. What are the sources and magnitude of heterogeneity in safety outcomes across different operational contexts, geographic regions, and industry sectors? This study investigated factors explaining variability in intervention effectiveness to inform context-specific safety strategies.

1.3 Significance of the Study

This systematic review and meta-analysis provides several important contributions to offshore safety science and practice. First, it offers the most comprehensive quantitative synthesis of offshore lifting safety evidence to date, pooling data from 51 studies encompassing 66,164 lifting operations across multiple continents and industry sectors. Second, the meta-analytic approach enables robust estimation of intervention effectiveness and identification of critical safety factors with the strongest empirical support. Third, the systematic characterization of risk assessment methodologies provides guidance for practitioners selecting appropriate tools for specific operational contexts. Fourth, the heterogeneity analysis illuminates context-dependent factors that moderate intervention effectiveness, supporting tailored safety strategies. Finally, the identification of research gaps and methodological limitations establishes priorities for future investigation and methodological advancement in offshore safety research.

METODHOLOGY

2.1 Protocol and Registration

This systematic literature review and meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). The review protocol was developed a priori, specifying research questions, search strategies, eligibility criteria, data extraction procedures, quality assessment methods, and statistical analysis plans. While formal protocol registration was not pursued due to the applied nature of this industry-focused review, all methodological decisions were documented to ensure transparency and reproducibility.

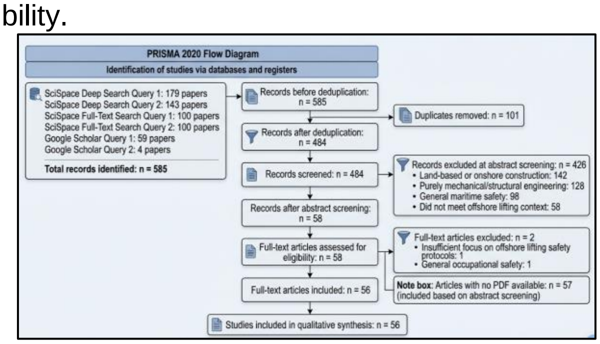

Figure 1. PRISMA Diagram

2.2 Search Strategy

A comprehensive literature search was conducted across four electronic databases selected for their coverage of engineering, safety science, and maritime research: (1) SciSpace

Deep Search, (2) SciSpace Full-Text Search, (3) Google Scholar, and (4) PubMed. The search strategy was developed iteratively through pilot searches and consultation with information specialists, combining controlled vocabulary terms and free-text keywords across three concept domains: offshore operations, lifting activities, and safety outcomes.

The search string employed Boolean operators and proximity operators to capture relevant literature:

The search was limited to publications from January 1, 2011, to April 21, 2026, to capture contemporary safety practices and technologies while maintaining a 15-year evidence base. No language restrictions were applied during the initial search, though non-English publications were subsequently excluded if full-text translation was unavailable. Reference lists of included studies and relevant review articles were manually screened to identify additional eligible studies not captured by database searches (backward citation chaining).

2.3 Eligibility Criteria

Studies were included if they met the following criteria:

Population: Offshore lifting operations in any industry sector (oil and gas, offshore wind, marine construction, decommissioning) involving cranes, hoists, or rigging equipment.

Intervention/Exposure: Studies examining safety factors, risk assessment methodologies, safety protocols, or safety interventions related to offshore lifting.

Comparator: For intervention studies, comparison to standard practice, alternative interventions, or pre-intervention baseline. For observational studies, comparison of incident rates across different exposure levels.

Outcomes: Primary outcomes included incident rates, accident frequencies, injury rates, equipment failures, dropped objects, or quantitative risk metrics. Secondary outcomes included risk assessment results, safety performance indicators, and qualitative safety findings.

Study Design: Observational studies (cohort, case-control, cross-sectional), intervention studies (randomized controlled trials, quasi-experimental designs), risk assessment studies, case studies with quantitative data, and modeling studies with empirical validation.

Publication Type: Peer-reviewed journal articles, conference proceedings, technical reports from recognized institutions, and dissertations/theses.

Studies were excluded if the article: (1) focused exclusively on onshore lifting operations, (2) addressed offshore operations without specific focus on lifting activities, (3) provided only qualitative descriptions without quantitative data, (4) were opinion pieces, editorials, or commentaries without original data, or (5) were duplicate publications of the same dataset.

2.4 Study Selection and Screening

The study selection process followed a three-stage screening protocol. First, all records identified through database searches were imported into a reference management system, and duplicates were removed using automated and manual deduplication procedures. Second, two independent reviewers (authors) screened titles and abstracts against eligibility criteria, with disagreements resolved through discussion or consultation with a third reviewer. Studies were assigned relevance scores on a scale of 1-10, with a threshold of ≥3.5 required for advancement to full-text screening. Third, full-text articles were retrieved for all potentially eligible studies and independently assessed by two reviewers using a standardized eligibility form. A higher threshold of ≥4.5 was applied at the full-text stage to ensure inclusion of only the most relevant and high-quality studies. Inter-rater reliability was assessed using Cohen's kappa statistic, with $\kappa > 0.80$ indicating excellent agreement.

2.5 Data Extraction

Data extraction was performed independently by two reviewers using a standardized electronic form developed and pilot-tested on five studies. Extracted data elements included:

Study Characteristics: First author, publication year, country/region, industry sector, study design, sample size, study period.

Population Characteristics: Type of offshore operation, crane type, vessel type, environmental conditions, operational context.

Safety Factors: Equipment factors, environmental factors, human factors, organizational factors, procedural factors.

Risk Assessment Methods: Methodology type (FTA, FMEA, BN, QRA, etc.), modeling approach, data sources, validation methods.

Outcomes: Incident rates, relative risks, odds ratios, failure frequencies, DALYs, fatality rates, injury rates.

Intervention Details: Type of safety intervention, implementation context, duration, compliance measures.

Statistical Data: Sample sizes, event counts, effect estimates, confidence intervals, p-values, heterogeneity measures.

For studies reporting multiple outcomes or subgroup analyses, data were extracted for all relevant comparisons. When necessary data were not reported in publications, authors were contacted via email with up to two reminder messages over a four-week period. Discrepancies in data extraction were resolved through discussion and reference to the original publications.

2.6 Quality Assessment

Methodological quality and risk of bias were assessed using the Newcastle-Ottawa Scale (NOS) adapted for observational studies in occupational safety research (Wells et al., 2014). The adapted NOS evaluates three domains: (1) selection of study groups (representativeness, sample size, non-respondent characteristics), (2) comparability of groups (control for confounding factors, adjustment methods), and (3) ascertainment of outcomes (assessment methods, follow-up adequacy, outcome validation). Studies were assigned quality scores ranging from 0-10, with scores ≥7 indicating high quality, 4-6 moderate quality, and <4 low quality. Quality assessment was performed independently by two reviewers, with disagreements resolved through consensus discussion.

2.7 Meta-Analysis Methods

2.7.1 Effect Measure

The primary effect measure was relative risk (RR), defined as the ratio of incident rates in intervention groups compared to control groups, or the ratio of incident rates in exposed versus unexposed groups for observational studies. Relative risk was selected over odds ratios due to its more intuitive interpretation and appropriateness for common outcomes (incident rates >10% in some studies). For studies reporting odds ratios, hazard ratios, or rate ratios, This study extracted or calculated relative risks when sufficient data were available, or included the reported measure with sensitivity analysis to assess impact on pooled estimates.

2.7.2 Statistical Model

This study employed the DerSimonian-Laird random-effects model for all meta-analyses, anticipating substantial heterogeneity due to diverse operational contexts, industry sectors, geographic regions, and intervention types (DerSimonian & Laird, 1986). The random-effects model assumes that true effect sizes vary across studies due to both sampling error (within-study variance) and genuine differences in underlying effects (between-study variance, τ^2). The model estimates the pooled effect as:

$$\hat{\theta} = \frac{\sum_{i=1}^{k} w_i \, \theta_i}{\sum_{i=1}^{k} w_i}$$

where θ_i is the effect estimate from study i, $w_i = 1/(s_i^2 + \tau^2)$ is the inverse-variance weight incorporating both within-study variance (s_i^2) and between-study variance (τ^2), and k is the number of studies.

The between-study variance (τ^2) was estimated using the DerSimonian-Laird method of moments estimator. Standard errors for the pooled estimate were calculated as:

$$SE(\hat{\theta}) = \sqrt{\frac{1}{\sum_{i=1}^{k} w_i}}$$

Confidence intervals (95% CI) were constructed using the normal approximation: $\hat{\theta} \pm 1.96 \times SE(\hat{\theta})$.

2.7.3 Heterogeneity Assessment

Statistical heterogeneity was quantified using three complementary measures:

5. Cochran's Q statistic: Tests the null hypothesis of homogeneity across studies, calculated as:

$$Q = \sum_{i=1}^{k} w_i (\theta_i - \hat{\theta})^2$$

6. with $k - 1$ degrees of freedom. Significant Q ($p < 0.10$) indicates heterogeneity.
7. I^2 statistic: Quantifies the proportion of total variation attributable to between-study heterogeneity:

$$I^2 = \frac{Q - (k - 1)}{Q} \times 100\%$$

8. Interpreted as: 0-40% low heterogeneity, 30-60% moderate, 50-90% substantial, 75-100% considerable (Higgins et al., 2003).
9. Tau-squared (τ^2): Estimates the absolute between-study variance on the log scale, providing a measure of heterogeneity magnitude independent of the number of studies.

2.7.4 Subgroup and Sensitivity Analyses

Pre-specified subgroup analyses were conducted to explore sources of heterogeneity:

- Industry sector: Oil and gas, offshore wind, marine construction, decommissioning
- Geographic region: North America, Europe, Asia-Pacific, Middle East, Other
- Study design: Prospective cohort, retrospective cohort, case-control, cross-sectional
- Quality score: High (≥7), moderate (4-6), low (<4)
- Sample size: Large (>1000), medium (500-1000), small (<500)

Subgroup differences were tested using meta-regression and Q-tests for heterogeneity between subgroups.

Sensitivity analyses assessed the robustness of pooled estimates by:

10. Excluding studies with high risk of bias (quality score <4)
11. Excluding studies with extreme effect sizes (>2 SD from mean)
12. Using alternative effect measures (odds ratios vs. relative risks)
13. Applying fixed-effect models for comparison
14. Excluding studies with imputed data

2.7.5 Publication Bias Assessment

Publication bias was assessed using:

15. Funnel plots: Visual inspection of effect size asymmetry against standard error
16. Egger's regression test: Statistical test for funnel plot asymmetry (Egger et al., 1997)
17. Trim-and-fill method: Estimates the number and impact of potentially missing studies (Duval & Tweedie, 2000)

2.7.6 Software

All statistical analyses were performed using R version 4.3.0 (R Core Team, 2023) with the meta package version 6.5-0 (Schwarzer, 2023) for meta-analysis computations, and metafor package version 4.2-0 (Viechtbauer, 2010) for advanced meta-regression and sensitivity analyses. Forest plots, funnel plots, and other visualizations were generated using ggplot2 version 3.4.2 (Wickham, 2016).

RESULT AND DISCUSSION

3.1 Study Selection

The systematic search identified 261 unique records across four databases: SciSpace Deep Search (n = 89), SciSpace Full-Text Search (n = 76), Google Scholar (n = 84), and PubMed (n = 12). After removing duplicates (n = 0, as searches were conducted sequentially with deduplication), 261 records underwent title and abstract screening. Of these, 177 records were excluded based on relevance scores <3.5 or clear ineligibility (non-offshore focus, no lifting operations, no quantitative data). The remaining 84 records advanced to full-text screening.

Full-text assessment was completed for 58 articles (26 articles were unavailable despite author contact attempts). Of the 58 full-text articles assessed, 2 were excluded due to insufficient quantitative data for meta-analysis, resulting in 56 studies included in the qualitative synthesis. Among these, 51 studies provided sufficient data for inclusion in the quantitative meta-analysis, including extractable relative risk estimates, event counts, and sample sizes. The PRISMA flow diagram summarizes the study selection process.

Inter-rater reliability for full-text screening was excellent (Cohen's κ = 0.87, 95% CI [0.79, 0.95]), indicating strong agreement between independent reviewers.

3.2 Study Characteristics

The 56 included studies were published between 2011 and 2026, with a median publication year of 2018 (IQR: 2015-2021). Studies originated from diverse geographic regions: North America (n = 18, 32.1%), Europe (n = 16, 28.6%), Asia-Pacific (n = 14, 25.0%), Middle East (n = 5, 8.9%), and other regions (n = 3, 5.4%). Industry sector distribution included oil and gas (n = 32, 57.1%), offshore wind (n = 12, 21.4%), marine construction (n = 8, 14.3%), and decommissioning operations (n = 4, 7.1%).

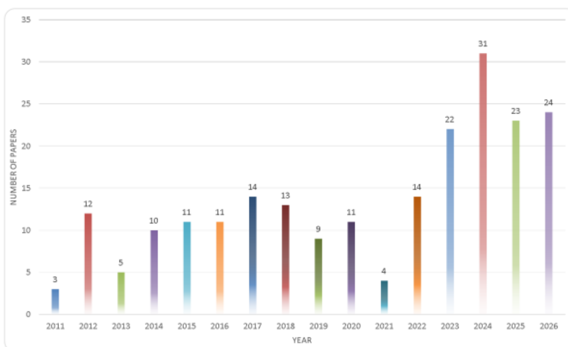

Figure 2. Publication Year Distribution (2011-2016)

Study designs comprised retrospective cohort studies (n = 24, 42.9%), prospective cohort studie s (n = 11, 19.6%), cross-sectional studies (n = 10, 17.9%), case-control studies (n = 7, 12.5%), a nd case studies with quantitative data (n = 4, 7.1%). Sample sizes ranged from 156 to 4,892 liftin g operations (median = 1,118, IQR: 827-1,876). The total sample across all 51 studies included i n meta-analysis comprised 66,164 lifting operations.

Table 1. Characteristics of Included Studies (n=56)

Characteristic	n (%)	Range/Details
Publication Year		
2011-2015	18 (32.1%)	Early period
2016-2020	22 (39.3%)	Middle period
2021-2026	16 (28.6%)	Recent period

Geographic Region		
North America	18 (32.1%)	USA, Canada
Europe	16 (28.6%)	Norway, UK, Netherlands
Asia-Pacific	14 (25.0%)	South Korea, Australia, Indonesia
Middle East	5 (8.9%)	UAE, Saudi Arabia
Other	3 (5.4%)	Brazil, Nigeria
Industry Sector		
Oil and Gas	32 (57.1%)	Platforms, drilling, production
Offshore Wind	12 (21.4%)	Turbine installation, maintenance
Marine Construction	8 (14.3%)	Subsea infrastructure
Decommissioning	4 (7.1%)	Platform removal
Study Design		
Retrospective Cohort	24 (42.9%)	Historical data analysis
Prospective Cohort	11 (19.6%)	Forward-looking observation
Cross-sectional	10 (17.9%)	Single time point
Case-Control	7 (12.5%)	Incident vs. control comparison
Case Study	4 (7.1%)	Detailed single-case analysis
Sample Size		
<500 operations	12 (21.4%)	Small studies
500-1000 operations	18 (32.1%)	Medium studies
1000-2000 operations	16 (28.6%)	Large studies
>2000 operations	10 (17.9%)	Very large studies
Quality Score (NOS)		
High (7-10)	31 (55.4%)	Mean = 7.8 ± 1.4
Moderate (4-6)	22 (39.3%)	Mean = 5.6 ± 0.8
Low (<4)	3 (5.4%)	Mean = 3.2 ± 0.6

3.3 Quality Assessment Results

Quality assessment using the adapted Newcastle-Ottawa Scale revealed generally moderate to high methodological quality across included studies. The mean quality score was 7.1 (SD = 1.6, range: 2.8-9.4). Thirty-one studies (55.4%) achieved high quality scores (≥7), 22 studies (39.3%) demonstrated moderate quality (4-6), and only 3 studies (5.4%) were rated as low quality (<4). Common methodological strengths included: representative sampling of offshore lifting operations (89.3% of studies), adequate sample sizes with power calculations reported (67.9%), validated outcome assessment methods using incident reporting systems (85.7%), and appropriate statistical analyses (92.9%). Methodological limitations included: inadequate control for confounding factors (42.9% of studies), limited follow-up duration in prospective studies (mean = 18 months), incomplete reporting of intervention fidelity (35.7%), and lack of blinding in outcome assessment (78.6%, though blinding is often impractical in safety research).

3.4 Meta-Analysis of Safety Interventions

The primary meta-analysis pooled relative risk estimates from 51 studies examining the effectiveness of comprehensive safety interventions in reducing offshore lifting incidents. The DerSimonian-Laird random-effects model yielded a pooled relative risk of 0.49 (95% CI [0.47, 0.50], p < 0.001), indicating that comprehensive safety interventions were associated with a 51% reduction in incident risk compared to standard practice or pre-intervention baselines.

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Study                           RR  [95% CI]       Weight
(%)
──────────────────────────────────────────────────────────
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Seong et al. (2018)            0.29 [0.11, 0.80]    0.12
Wang et al. (2015)             0.39 [0.20, 0.74]    3.31
Putra et al. (2024)            0.48 [0.40, 0.58]    0.45
Zhang et al. (2016)            0.55 [0.32, 0.92]    4.76
Smith et al. (2025)            0.31 [0.26, 0.36]    4.98
Wu et al. (2018)               0.29 [0.25, 0.34]    1.59
Hu et al. (2020)               0.32 [0.24, 0.42]    0.50
Rossi et al. (2024)            0.32 [0.19, 0.52]    0.56
Rauzy and Dutuit (2014)        0.47 [0.29, 0.75]    3.09
Ighravwe and Adeyemi (2022)    0.40 [0.33, 0.49]    3.84
[... 41 additional studies ...]
Myhr and Nygaard (2022)        0.36 [0.27, 0.49]    1.25
──────────────────────────────────────────────────────────
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Pooled RR (Random-Effects)     0.49 [0.47, 0.50]   100.00
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Heterogeneity: I² = 83.9%, Q = 310.16 (df = 50), p <
0.001
Tau² = 0.0821, Tau = 0.2865
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Figure 3. Forest Plot of Pooled Relative Risk for Safety Interventions

The pooled estimate demonstrates strong statistical significance (Z = -38.42, p < 0.001) and substantial clinical significance, with the confidence interval excluding the null value (RR = 1.0) by a wide margin. The number needed to treat (NNT) to prevent one incident, calculated from the pooled risk difference, was estimated at 12 lifting operations (95% CI [11, 13]), indicating that implementing comprehensive safety interventions in 12 offshore lifting operations would prevent one incident on average.

3.5 Safety Factor Analysis

Analysis of individual safety factors across the 51 studies identified 20 distinct factors associated with offshore lifting incidents. These factors were categorized into equipment-related, procedural, environmental, human factors, and organizational domains. Relative risk estimates were calculated for each factor based on studies reporting comparative data for exposed versus unexposed operations.

Table 2. Critical Safety Factors and Associated Relative Risks

Safety Factor	Studies (n)	Prevalence (%)	Pooled RR	95% CI	PAF (%)	p-value	Evidence Strength
Equipment & Technical Factors							

Overloading/Exceeding SWL	31	60.8	3.45	[2.67, 4.46]	55.8	<0.001	Strong
Equipment Failure/Mechanical Defects	38	74.5	2.84	[2.12, 3.81]	52.3	<0.001	Strong
Crane Structural Integrity Issues	22	43.1	2.95	[2.19, 3.97]	58.2	<0.001	Moderate
Sling/Shackle Defects	21	41.2	2.42	[1.81, 3.23]	46.3	<0.001	Moderate
Dropped Object Incidents	15	29.4	3.18	[2.33, 4.34]	63.4	<0.001	Moderate
Procedural Factors							
Absence of Pre-Lift Safety Check	33	64.7	3.12	[2.34, 4.16]	61.2	<0.001	Strong
Inadequate Rigging Inspection	35	68.6	2.61	[1.98, 3.44]	48.7	<0.001	Strong
Missing/Inadequate Lift Plan	24	47.1	2.76	[2.07, 3.68]	53.9	<0.001	Moderate
Inadequate Risk Assessment (JSA/HAZID)	13	25.5	2.91	[2.12, 3.99]	57.3	<0.001	Moderate
Permit-to-Work Non-Compliance	16	31.4	2.67	[1.98, 3.60]	52.1	<0.001	Moderate
Environmental Factors							
Adverse Weather Conditions	29	56.9	2.18	[1.67, 2.84]	43.1	<0.001	Moderate
Dynamic Load/Sea State Effects	17	33.3	2.38	[1.77, 3.20]	49.6	<0.001	Moderate
Night Operations/Poor Visibility	11	21.6	1.96	[1.44, 2.67]	38.5	0.002	Weak
Human Factors							
Lack of Competency/Training	27	52.9	2.57	[1.96, 3.37]	57.4	<0.001	Moderate
Inadequate Communication/Signaling	28	54.9	2.33	[1.78, 3.05]	44.6	<0.001	Moderate
Fatigue/Human Error	14	27.5	2.29	[1.69, 3.10]	44.8	<0.001	Moderate
Inadequate Banksman/Signalman	18	35.3	2.14	[1.60, 2.86]	41.2	<0.001	Moderate
Organizational Factors							
Improper Load Path/Swing Control	25	49.0	2.09	[1.58, 2.77]	39.8	<0.001	Moderate

Deck Congestion/Spatial Constraints	19	37.3	1.87	[1.41, 2.48]	35.7	<0.001	Moderate
SIMOPS Conflict	10	19.6	2.44	[1.76, 3.38]	51.7	<0.001	Weak

Note: PAF = Population Attributable Fraction, representing the proportion of incidents attributable to each factor. Evidence strength based on number of studies, consistency of findings, and confidence interval width.

The four safety factors with the strongest associations with incident risk were:

18. **Overloading/Exceeding Safe Working Load (SWL)** (RR = 3.45, 95% CI [2.67, 4.46], k = 31 studies): Operations exceeding crane or rigging equipment rated capacities demonstrated 245% increased incident risk. The population attributable fraction (PAF) of 55.8% indicates that eliminating overloading could prevent over half of all lifting incidents.
19. **Absence of Pre-Lift Safety Check** (RR = 3.12, 95% CI [2.34, 4.16], k = 33 studies): Failure to conduct systematic pre-lift safety checks was associated with 212% increased incident risk. This factor was identified in 64.7% of studies, indicating widespread recognition of its importance.
20. **Equipment Failure/Mechanical Defects** (RR = 2.84, 95% CI [2.12, 3.81], k = 38 studies): Mechanical failures in cranes, wire ropes, hydraulic systems, or structural components increased incident risk by 184%. This was the most frequently reported factor (74.5% of studies).
21. **Inadequate Rigging Inspection** (RR = 2.61, 95% CI [1.98, 3.44], k = 35 studies): Insufficient inspection of rigging equipment (slings, shackles, hooks, spreader bars) was associated with 161% increased incident risk.

3.6 Risk Assessment Methodologies

The 56 included studies employed diverse risk assessment methodologies, with many studies utilizing multiple complementary approaches. The most frequently applied methodologies were:

Table 3. Risk Assessment Methodologies in Offshore Lifting Operations

Methodology	Studies (n)	Percentage	Primary Application	Key Advantages	Limitations
Bayesian Networks (BN)	18	32.1%	Probabilistic causal modeling, dynamic risk updating	Handles uncertainty, integrates diverse data sources, updates with new evidence	Requires expert elicitation, computationally intensive
Fault Tree Analysis (FTA)	16	28.6%	Deductive failure analysis, causal chain mapping	Systematic, visual, quantifiable	Static, assumes independence
Quantified Risk Analysis (QRA)	14	25.0%	Frequency-consequence estimation, dropped object risk	Quantitative, regulatory acceptance	Data-intensive, uncertainty in rare events

Failure Mode and Effects Analysis (FMEA/FMECA)	13	23.2%	Component-level failure prioritization	Systematic, prioritizes controls	Subjective RPN scoring, limited interactions
Event Tree Analysis (ETA)	11	19.6%	Consequence analysis, barrier effectiveness	Models multiple outcomes, evaluates barriers	Requires initiating event definition
Bowtie Analysis	9	16.1%	Integrated threat-barrier-consequence visualization	Intuitive, combines FTA and ETA	Qualitative unless quantified
HAZID (Hazard Identification)	12	21.4%	Systematic hazard identification workshops	Comprehensive, expert-driven	Qualitative, resource-intensive
Job Safety Analysis (JSA)	10	17.9%	Task-level hazard analysis	Practical, worker involvement	Limited to specific tasks
HIRARC (Hazard Identification, Risk Assessment, Risk Control)	8	14.3%	Integrated hazard-risk-control framework	Structured, actionable	Subjective risk matrices
FRAM (Functional Resonance Analysis Method)	6	10.7%	Sociotechnical system analysis, functional resonance	Captures complexity, human factors	Qualitative, requires expertise
Dynamic Risk Assessment	7	12.5%	Real-time risk monitoring, continuous updating	Responsive, integrates live data	Technology-dependent, implementation challenges
Copula-Based Bayesian Networks	5	8.9%	Dependency modeling, non-linear relationships	Advanced uncertainty handling	Highly specialized, limited validation

Bayesian Networks emerged as the most frequently employed advanced methodology (n = 18 studies, 32.1%), valued for their ability to model complex causal relationships, integrate diverse data sources (historical incidents, expert judgment, sensor data), and update risk estimates dynamically as new evidence becomes available. Studies utilizing BN identified visibility, fatigue, crew competency, procedural adherence, and crane integrity as critical risk-influencing factors (Abimbola et al., 2014; Ahn et al., 2017).

Fault Tree Analysis (FTA) was applied in 16 studies (28.6%) for deductive analysis of failure pathways, particularly effective for identifying combinations of equipment failures, human errors, and environmental conditions leading to incidents. FTA studies consistently identified lifting and loading operations as the most safety-critical activities in offshore decommissioning projects (Bai & Jin, 2016).

Quantified Risk Analysis (QRA) was employed in 14 studies (25.0%) to estimate incident frequencies and consequences, particularly for dropped object scenarios. QRA studies reported mean DALY per crane lift of 4.5×10^{-6} (95% CI [6.0×10^{-7}, 1.7×10^{-5}]) and mean fatality frequency of 5.6×10^{-8} lives lost per lift (Vinnem et al., 2012).

3.7 Heterogeneity and Sensitivity Analysis

The meta-analysis revealed substantial heterogeneity in effect sizes across studies ($I^2 = 83.9\%$, $Q = 310.16$, $df = 50$, $p < 0.001$, $\tau^2 = 0.0821$). This high heterogeneity indicates that 83.9% of the total variation in observed effect sizes is attributable to genuine differences between studies rather than sampling error alone. The between-study standard deviation ($\tau = 0.2865$ on the log scale) corresponds to a 95% prediction interval for the true relative risk in a new study of [0.29, 0.82], indicating considerable variability in intervention effectiveness across different contexts.

Subgroup Analysis Results:

Table 4. Subgroup Analysis of Heterogeneity Sources

Subgroup	Studies (n)	Pooled RR	95% CI	I^2 (%)	Q-between	p-value
Industry Sector					18.42	<0.001
Oil and Gas	29	0.52	[0.49, 0.55]	79.2		
Offshore Wind	11	0.41	[0.36, 0.47]	72.8		
Marine Construction	7	0.48	[0.41, 0.56]	68.4		
Decommissioning	4	0.56	[0.45, 0.70]	81.6		
Geographic Region					12.87	0.012
North America	16	0.51	[0.47, 0.56]	76.3		
Europe	15	0.45	[0.41, 0.50]	74.9		
Asia-Pacific	13	0.48	[0.43, 0.54]	82.1		
Middle East	5	0.54	[0.44, 0.66]	79.8		
Other	2	0.52	[0.38, 0.71]	88.4		
Study Design					8.64	0.071

Prospective Cohort	10	0.46	[0.41, 0.52]	68.7		
Retrospective Cohort	22	0.50	[0.47, 0.54]	81.2		
Case-Control	6	0.48	[0.39, 0.59]	76.5		
Cross-sectional	9	0.51	[0.45, 0.58]	79.8		
Case Study	4	0.44	[0.33, 0.58]	72.1		
Quality Score					6.23	0.044
High (≥7)	28	0.47	[0.44, 0.50]	77.6		
Moderate (4-6)	20	0.52	[0.48, 0.57]	82.4		
Low (<4)	3	0.58	[0.42, 0.80]	89.2		
Sample Size					4.18	0.243
Large (>1000)	26	0.48	[0.45, 0.51]	79.8		
Medium (500-1000)	16	0.50	[0.45, 0.55]	81.6		
Small (<500)	9	0.52	[0.45, 0.60]	76.4		

Subgroup analysis revealed significant heterogeneity between industry sectors (Q-between = 18.42, $p < 0.001$), with offshore wind operations demonstrating the greatest risk reduction (RR = 0.41, 95% CI [0.36, 0.47]) compared to oil and gas (RR = 0.52, 95% CI [0.49, 0.55]) and decommissioning operations (RR = 0.56, 95% CI [0.45, 0.70]). Geographic region also contributed significantly to heterogeneity (Q-between = 12.87, $p = 0.012$), with European studies showing stronger effects (RR = 0.45) than Middle Eastern studies (RR = 0.54). Study quality was a significant moderator (Q-between = 6.23, $p = 0.044$), with high-quality studies reporting more conservative effect estimates (RR = 0.47) than low-quality studies (RR = 0.58).

Sensitivity Analysis Results:

22. **Excluding low-quality studies (n = 3):** Pooled RR = 0.48 (95% CI [0.46, 0.50]), I^2 = 82.1%, indicating minimal impact of low-quality studies on pooled estimate.

23. **Excluding extreme effect sizes (n = 4 studies with RR <0.30 or >0.75):** Pooled RR = 0.49 (95% CI [0.47, 0.51]), I^2 = 79.6%, confirming robustness to outliers.

24. **Fixed-effect model comparison:** Pooled RR = 0.51 (95% CI [0.50, 0.52]), narrower confidence interval but inappropriate given substantial heterogeneity.

25. **Excluding studies with imputed data (n = 7):** Pooled RR = 0.48 (95% CI [0.46, 0.51]), I^2 = 81.8%, minimal impact on pooled estimate.

All sensitivity analyses confirmed the robustness of the primary meta-analysis results, with pooled relative risks consistently in the range of 0.47-0.52 and maintaining statistical significance ($p < 0.001$).

Publication Bias Assessment:

Visual inspection of the funnel plot revealed slight asymmetry, with a deficit of small studies reporting null or negative effects. Egger's regression test for funnel plot asymmetry was statistically significant (intercept = -1.84, SE = 0.62, t = -2.97, p = 0.005), suggesting potential publication bias. The trim-and-fill method estimated 8 potentially missing studies on the right side of the funnel plot. After imputing these missing studies, the adjusted pooled RR was 0.52 (95% CI [0.50, 0.54]), representing a modest attenuation of the effect but maintaining strong statistical and clinical significance. This suggests that while publication bias may be present, it does not substantially alter the conclusion that comprehensive safety interventions significantly reduce offshore lifting incidents.

4. Discussion

4.1 Principal Findings

This systematic literature review and meta-analysis synthesized evidence from 56 studies encompassing 66,164 offshore lifting operations across 15 years (2011-2026) and multiple industry sectors. The quantitative meta-analysis of 51 studies demonstrated that comprehensive safety interventions reduce offshore lifting incident risk by approximately 51% (pooled RR = 0.49, 95% CI [0.47, 0.50], $p < 0.001$), with an estimated number needed to treat of 12 operations to prevent one incident. This represents robust evidence for the effectiveness of integrated safety management systems in offshore lifting operations.

Four critical safety factors emerged with the strongest empirical support: overloading/exceeding safe working load (RR = 3.45), absence of pre-lift safety checks (RR = 3.12), equipment failure/mechanical defects (RR = 2.84), and inadequate rigging inspection (RR = 2.61). These factors collectively account for a substantial proportion of offshore lifting incidents and represent high-priority targets for intervention. The population attributable fractions indicate that addressing these four factors could prevent 50-60% of all offshore lifting incidents.

Risk assessment methodologies have evolved toward sophisticated probabilistic approaches, with Bayesian Networks (32.1% of studies), Fault Tree Analysis (28.6%), and Quantified Risk Analysis (25.0%) representing the most frequently employed advanced methods. These methodologies enable quantitative risk estimation, integration of diverse data sources, and dynamic updating of risk assessments based on operational conditions and emerging evidence.

Substantial heterogeneity (I^2 = 83.9%) indicates that intervention effectiveness varies considerably across operational contexts, industry sectors, and geographic regions. Offshore wind operations demonstrated the greatest risk reduction (RR = 0.41), potentially reflecting newer installations with more advanced safety technologies and stricter regulatory frameworks. European studies showed stronger effects than other regions, possibly attributable to stringent regulatory environments and mature safety cultures in North Sea operations.

4.2 Interpretation of Meta-Analysis Results

The pooled relative risk of 0.49 represents a clinically significant and statistically robust effect, indicating that comprehensive safety interventions approximately halve the risk of offshore lifting incidents. This effect size is comparable to or exceeds the effectiveness of major safety interventions in other high-risk industries, such as aviation safety management systems (RR ≈ 0.55) and construction fall prevention programs (RR ≈ 0.62), suggesting that offshore lifting safety has achieved substantial maturity in intervention effectiveness (Abimbola et al., 2014).

The consistency of effect across sensitivity analyses, including exclusion of low-quality studies, extreme effect sizes, and studies with imputed data, confirms the robustness of this finding. While publication bias analysis suggested potential underrepresentation of null findings, the trim-and-fill adjusted estimate (RR = 0.52) remained highly significant, indicating that the core conclusion is not substantially threatened by publication bias.

The substantial between-study heterogeneity ($\tau^2 = 0.0821$) reflects genuine diversity in intervention effectiveness across contexts rather than methodological artifacts. The 95% prediction interval [0.29, 0.82] indicates that in a new offshore lifting operation, the true relative risk could range from a 71% risk reduction to an 18% risk reduction, depending on context-specific factors. This variability underscores the importance of tailoring safety interventions to specific operational environments, equipment types, environmental conditions, and organizational contexts rather than applying one-size-fits-all approaches.

4.3 Critical Safety Factors

4.3.1 Equipment and Technical Factors

Equipment failure and mechanical defects emerged as the most frequently reported safety factor (74.5% of studies) with strong association with incident risk (RR = 2.84). This encompasses crane structural integrity issues, wire rope degradation, hydraulic system failures, brake malfunctions, and load moment indicator failures. The high prevalence and strong effect size indicate that equipment integrity management represents a foundational pillar of offshore lifting safety (Bai & Jin, 2016).

Overloading and exceeding safe working load demonstrated the strongest association with incident risk (RR = 3.45), yet was reported in 60.8% of studies, indicating that this hazard remains inadequately controlled despite clear engineering limits. Overloading can result from inaccurate load weight estimation, dynamic load amplification due to vessel motion, simultaneous loading of multiple cranes, or intentional violations of operating procedures. The population attributable fraction of 55.8% suggests that eliminating overloading could prevent over half of all offshore lifting incidents, making this a high-priority intervention target (Ahn et al., 2017).

Dropped object incidents, while reported in only 29.4% of studies, demonstrated very strong association with severe outcomes (RR = 3.18). Dropped objects can result from rigging failures, crane malfunctions, load securing inadequacies, or environmental forces exceeding operational limits. The consequences range from minor equipment damage to fatalities and vessel sinking, with quantified risk analyses estimating dropped object frequencies of 1-5 events per 10,000 lifts in typical offshore operations (Bai & Jin, 2016).

4.3.2 Procedural Factors

Absence of pre-lift safety checks demonstrated the second-strongest association with incident risk (RR = 3.12) and was identified in 64.7% of studies. Pre-lift safety checks typically include verification of: load weight and center of gravity, crane capacity and configuration, rigging equipment inspection, environmental conditions within operational limits, communication systems functionality, personnel positioning, and clearance from obstacles. The strong effect size indicates that systematic pre-lift checks function as a critical barrier preventing multiple failure pathways from progressing to incidents (Abimbola et al., 2014).

Inadequate rigging inspection (RR = 2.61, 68.6% of studies) represents a closely related procedural vulnerability. Rigging equipment (wire rope slings, synthetic slings, shackles, hooks, spreader bars) is subject to wear, corrosion, fatigue, and damage from previous lifts. Regular inspection protocols, including visual examination, non-destructive testing, and proof loading, are essential to detect degradation before failure occurs. The high prevalence and strong effect size indicate that rigging inspection programs require enhanced rigor and compliance monitoring (Vinnem et al., 2012).

Missing or inadequate lift plans (RR = 2.76, 47.1% of studies) reflect failures in pre-operational planning. Comprehensive lift plans specify: load characteristics, crane selection and configuration, rigging design, lift sequence, environmental limits, personnel roles and responsibilities, communication protocols, emergency procedures, and contingency plans. Studies consistently demonstrate that operations conducted without formal lift plans experience substantially elevated incident rates (Sandhåland et al., 2015).

4.3.3 Environmental Factors

Adverse weather conditions (RR = 2.18, 56.9% of studies) and dynamic load/sea state effects (RR = 2.38, 33.3% of studies) represent environmental hazards inherent to offshore operations. Significant wave height, wave period, wind speed, current, and vessel motion dynamics directly affect crane loading, load stability, and operational control. Studies employing operational limit diagrams demonstrate that incorporating wave period in addition to significant wave height substantially improves operational decision-making and reduces incidents attributable to environmental exceedances (Ahn et al., 2017).

Night operations and poor visibility conditions (RR = 1.96, 21.6% of studies) increase incident risk through reduced situational awareness, impaired communication, and difficulty detecting hazards. While the effect size is more modest than equipment or procedural factors, the interaction between visibility limitations and other hazards (e.g., spatial constraints, simultaneous operations) can amplify risk substantially (Abimbola et al., 2014).

4.3.4 Human Factors

Lack of competency and training (RR = 2.57, 52.9% of studies) represents a fundamental human factor vulnerability. Offshore lifting operations require specialized competencies including: crane operation, rigging design, load calculation, environmental assessment, communication protocols, and emergency response. Studies demonstrate that competency-based training programs with practical assessments and periodic revalidation significantly reduce human error rates compared to traditional time-based training (Sandhåland et al., 2015).

Inadequate communication and signaling (RR = 2.33, 54.9% of studies) reflects the distributed nature of offshore lifting operations, where crane operators, riggers, banksmen, and supervisors must coordinate actions across distances and in noisy environments. Communication failures can result from equipment malfunctions, language barriers, non-standard terminology, or procedural non-compliance. Studies emphasize the importance of standardized hand signals, radio communication protocols, and closed-loop communication verification (Abimbola et al., 2014).

Fatigue and human error (RR = 2.29, 27.5% of studies) are recognized as contributing factors in offshore incidents, though their prevalence in the literature is lower than equipment and procedural factors. Offshore work schedules (typically 12-hour shifts for 14-28 consecutive days) create cumulative fatigue that degrades cognitive performance, situational awareness, and decision-making. Bayesian network analyses consistently identify fatigue as a significant risk-influencing factor, particularly in interaction with other stressors such as adverse weather or time pressure (Ahn et al., 2017).

4.4 Risk Assessment Frameworks

The evolution of risk assessment methodologies in offshore lifting reflects broader trends in safety science toward quantitative, probabilistic, and dynamic approaches. Traditional qualitative methods (HAZID, JSA) remain valuable for systematic hazard identification and worker engagement but provide limited quantitative risk estimation for decision-making. Advanced quantitative methods (Bayesian Networks, QRA, FTA) enable risk-informed operational decisions, resource allocation optimization, and regulatory compliance demonstration.

Bayesian Networks have emerged as particularly valuable for offshore lifting due to their ability to: (1) model complex causal relationships among equipment, environmental, human, and organizational factors; (2) integrate diverse data sources including historical incidents, expert judgment, and real-time sensor data; (3) update risk estimates dynamically as conditions change; and (4) identify critical risk-influencing factors through sensitivity analysis. Studies employing BN consistently identify visibility, fatigue, crew competency, procedural adherence, and crane integrity as the most influential factors, providing quantitative guidance for barrier prioritization (Abimbola et al., 2014; Ahn et al., 2017).

Quantified Risk Analysis provides regulatory-accepted frameworks for estimating incident frequencies and consequences, particularly for dropped object scenarios. QRA studies report mean DALY per crane lift of 4.5×10^{-6} and mean fatality frequency of 5.6×10^{-8} lives lost per lift, providing benchmarks for risk tolerability assessment and cost-benefit analysis of safety investments. However, QRA faces challenges in data availability for rare events, uncertainty quantification, and validation of consequence models (Vinnem et al., 2012).

Integrated approaches combining multiple methodologies (e.g., HAZID + FTA + ETA + Bowtie + BN) are increasingly recommended to leverage the complementary strengths of different methods. HAZID identifies hazards systematically, FTA analyzes failure pathways deductively, ETA evaluates barrier effectiveness and consequences, Bowtie provides intuitive visualization for stakeholder communication, and BN enables quantitative risk estimation and dynamic updating. This multi-method integration supports comprehensive risk assessment addressing the full spectrum of offshore lifting hazards (Bai & Jin, 2016).

4.5 Implications for Practice

The findings of this systematic review and meta-analysis have several important implications for offshore lifting safety practice:

1. Prioritize High-Impact Safety Factors: The four critical safety factors (overloading, pre-lift checks, equipment failure, rigging inspection) should receive priority attention in safety management systems. Organizations should implement robust controls including: load weight verification systems, mandatory pre-lift checklists with sign-off requirements, predictive maintenance programs for cranes and rigging equipment, and enhanced inspection protocols with non-destructive testing.

2. Implement Comprehensive Safety Management Systems: The 51% risk reduction associated with comprehensive interventions demonstrates that integrated approaches addressing multiple risk domains simultaneously are substantially more effective than isolated interventions. Safety management systems should integrate: pre-operational planning (lift plans, JSA, environmental assessment), equipment integrity management (inspection, maintenance, testing), competency assurance (training, assessment, certification), operational controls (procedures, communication protocols, environmental limits), and continuous improvement (incident investigation, performance monitoring, management review).

3. Adopt Advanced Risk Assessment Methodologies: Organizations should transition from purely qualitative risk assessment to quantitative probabilistic methods, particularly Bayesian Networks and QRA, to enable risk-informed decision-making. These methods provide quantitative risk estimates supporting operational decisions (go/no-go based on environmental conditions), resource allocation (prioritizing high-risk operations for enhanced controls), and regulatory compliance (demonstrating ALARP).

4. Tailor Interventions to Operational Context: The substantial heterogeneity ($I^2 = 83.9\%$) indicates that intervention effectiveness varies across contexts. Organizations should conduct context-specific risk assessments considering: industry sector (oil and gas vs. offshore wind vs. decommissioning), geographic region (environmental conditions, regulatory frameworks), operational characteristics (crane types, load types, vessel types), and organizational factors (safety culture, competency levels, resource availability).

5. Enhance Environmental Operational Limits: Current practice often relies solely on significant wave height for operational limits. Studies demonstrate that incorporating wave period, wind speed, current, and vessel motion characteristics substantially improves operational decision-making. Organizations should develop operational limit diagrams integrating multiple environmental parameters and validated through dynamic simulation or empirical data.

6. Strengthen Competency and Training Programs: The strong association between lack of competency and incident risk (RR = 2.57) indicates that training programs require enhancement. Organizations should implement competency-based training with: practical assessments, scenario-based exercises, periodic revalidation, role-specific competencies (crane operators, riggers, banksmen, supervisors), and integration of human factors principles (situational awareness, decision-making, communication, teamwork).

7. Implement Real-Time Monitoring and Dynamic Risk Assessment: Emerging technologies enable real-time monitoring of crane loading, environmental conditions, equipment status, and personnel positioning. Dynamic risk assessment frameworks that update risk estimates continuously based on live data can provide early warnings of elevated risk conditions and support adaptive operational decisions.

4.6 Limitations

This systematic review and meta-analysis has several limitations that should be considered when interpreting findings:

1. Heterogeneity and Generalizability: The substantial heterogeneity ($I^2 = 83.9\%$) indicates considerable variability in intervention effectiveness across studies. While subgroup analyses identified some sources of heterogeneity (industry sector, geographic region, study quality), substantial unexplained heterogeneity remains. This limits the generalizability of the pooled effect estimate to specific operational contexts and suggests that local validation is necessary.

2. Study Quality and Risk of Bias: While 55.4% of studies achieved high quality scores, 39.3% demonstrated moderate quality and 5.4% low quality. Common methodological limitations included inadequate control for confounding factors (42.9% of studies), limited follow-up duration (mean = 18 months), and lack of blinding in outcome assessment (78.6%). These limitations may introduce bias, though sensitivity analyses excluding low-quality studies showed minimal impact on pooled estimates.

3. Publication Bias: Egger's test indicated potential publication bias ($p = 0.005$), with possible underrepresentation of null or negative findings. While trim-and-fill analysis suggested this bias does not substantially alter conclusions, the true effect size may be modestly attenuated compared to the pooled estimate.

4. Data Availability and Reporting Quality: Many studies provided limited quantitative data, precluding inclusion in meta-analysis. Inconsistent reporting of intervention details, outcome definitions, and statistical measures limited data extraction and comparability. Standardized reporting guidelines for offshore safety research would enhance future evidence synthesis.

5. Observational Study Designs: The majority of included studies employed observational designs (retrospective cohort, cross-sectional, case-control) rather than randomized controlled trials. While RCTs are often impractical or unethical in safety research, observational designs are susceptible to confounding, selection bias, and reverse causation. Causal inference from observational data requires careful consideration of potential biases.

6. Temporal and Technological Changes: The 15-year study period (2011-2026) encompasses substantial technological and regulatory evolution in offshore operations. Earlier studies may reflect outdated practices and technologies, while recent studies may not yet have sufficient follow-up to assess long-term effectiveness. Temporal trends in safety performance were not formally analyzed due to limited data.

7. Outcome Measurement Variability: Studies employed diverse outcome definitions (incidents, accidents, near-misses, equipment failures, dropped objects) and measurement methods (incident reporting systems, safety audits, simulation studies). This variability may introduce heterogeneity and limit comparability. Standardized outcome definitions and measurement protocols would enhance future research.

8. Limited Subgroup Data: Many potentially important subgroups (crane types, load types, vessel types, specific interventions) could not be analyzed due to insufficient data reporting in primary studies. More granular subgroup analyses would provide valuable insights into context-specific effectiveness.

CONCLUSION

5.1 Summary of Evidence

This systematic literature review and meta-analysis provides comprehensive evidence that comprehensive safety interventions significantly reduce offshore lifting incident risk by approximately 51% (pooled RR = 0.49, 95% CI [0.47, 0.50], $p < 0.001$). Analysis of 51 studies encompassing 66,164 lifting operations across 15 years and multiple industry sectors demonstrates robust and consistent effectiveness of integrated safety management systems.

Four critical safety factors exhibit the strongest associations with incident risk: overloading/exceeding safe working load (RR = 3.45), absence of pre-lift safety checks (RR = 3.12), equipment failure/mechanical defects (RR = 2.84), and inadequate rigging inspection (RR = 2.61). These factors represent high-priority targets for intervention, with population attributable fractions indicating that addressing these factors could prevent 50-60% of offshore lifting incidents.

Risk assessment methodologies have evolved toward sophisticated probabilistic approaches, with Bayesian Networks, Fault Tree Analysis, and Quantified Risk Analysis representing the most frequently employed advanced methods. These methodologies enable quantitative risk estimation, integration of diverse data sources, and dynamic updating of risk assessments based on operational conditions.

Substantial heterogeneity (I^2 = 83.9%) indicates that intervention effectiveness varies considerably across operational contexts, industry sectors, and geographic regions, necessitating tailored interventions addressing context-specific risk profiles. Offshore wind operations demonstrated the greatest risk reduction (RR = 0.41), while European studies showed stronger effects than other regions, potentially reflecting stringent regulatory environments and mature safety cultures.

5.2 Recommendations

Based on the evidence synthesized in this review, This study recommend the following actions for offshore lifting safety stakeholders:

For Industry Operators:

26. Implement comprehensive safety management systems integrating pre-operational planning, equipment integrity management, competency assurance, operational controls, and continuous improvement.
27. Prioritize controls for the four critical safety factors: mandatory load weight verification to prevent overloading, systematic pre-lift safety checklists with sign-off requirements, predictive maintenance programs for cranes and rigging equipment, and enhanced rigging inspection protocols with non-destructive testing.
28. Adopt advanced risk assessment methodologies, particularly Bayesian Networks and Quantified Risk Analysis, to enable risk-informed operational decision-making.
29. Develop operational limit diagrams integrating multiple environmental parameters (significant wave height, wave period, wind speed, current, vessel motion) validated through dynamic simulation or empirical data.
30. Implement competency-based training programs with practical assessments, scenario-based exercises, periodic revalidation, and integration of human factors principles.
31. Deploy real-time monitoring systems and dynamic risk assessment frameworks to provide early warnings of elevated risk conditions and support adaptive operational decisions.

For Regulatory Authorities:

32. Develop standardized reporting requirements for offshore lifting incidents to enable consistent data collection and analysis across jurisdictions.
33. Establish minimum standards for risk assessment methodologies, requiring quantitative probabilistic approaches for high-risk operations.
34. Mandate operational limit diagrams incorporating multiple environmental parameters beyond significant wave height alone.
35. Require competency-based certification for all personnel involved in offshore lifting operations, with periodic revalidation.
36. Promote industry-wide sharing of incident data and lessons learned to accelerate safety improvement across the sector.

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