

Simulation-Based Safety Training for Power-Plant Maintenance: An Integrative Review of Safety Learning, Behavior, and Transferability to the Indonesian Context

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ABSTRACT

Background: Unsafe actions remain a safety concern in power-plant maintenance, but Indonesian field evidence linking simulation-based training to observed reductions is limited. **Purpose:** To integrate Indonesian evidence on unsafe-action determinants with international evidence on simulation/VR effects and assess transferability to Indonesian power-plant maintenance. **Methods:** An integrative review guided by Whittemore and Knafl searched multiple international and Indonesian databases and backward citations. PRISMA 2020 principles were selectively applied. Searches were rerun on 10 September 2026. Twelve peer-reviewed studies (three Indonesian and nine international) were appraised using design-appropriate JBI criteria. Heterogeneity precluded meta-analysis. **Results:** Among 69 Indonesian power-plant repair workers, 62.32% exhibited high unsafe-action levels. Low OSH knowledge (OR = 4.200, 95% CI: 1.481–11.913) and poor supervision (OR = 3.429, 95% CI: 1.194–9.848) were associated with unsafe actions. Among 50 Indonesian electrical workers, knowledge improved significantly in both intervention sequences involving VR ($p < 0.001$). International evidence generally favored simulation/VR for knowledge, hazard recognition, self-efficacy, and selected task performance, although long-term behavioral effects were inconsistent. **Conclusion:** Simulation-based safety training is a promising component of broader competency and safety-management systems, alongside supervision and competency verification. However, its causal effect on unsafe-action frequency among Indonesian power-plant maintenance workers remains unestablished, requiring controlled field trials with behavioral follow-up.

INTRODUCTION

Power-plant maintenance and overhaul combine electrical hazards, hot work, lifting, work at height, rotating equipment, confined spaces, stored energy, and time pressure. In these conditions, safe performance depends on more than knowing written procedures: workers must recognize hazards, select controls, sequence critical steps, communicate, and stop work when conditions



deviate from the permit or procedure. Indonesian evidence demonstrates that unsafe actions remains relevant in power-generation maintenance. Afifah et al. (2025) reported 68 unsafe actions and 49 accidents during 2022–2023 among engineering support workers in power-plant repair services and identified gaps in standard operating procedure understanding, hazard/risk knowledge, and supervision as important contributors.

The same study found that 43 of 69 workers (62.32%) were categorized as having high unsafe-action levels, 36 (52.17%) had low occupational safety and health (OSH) knowledge, and 31 (44.93%) rated OSH supervision as poor. Low OSH knowledge was associated with higher odds of unsafe action (OR = 4.200, 95% CI: 1.481–11.913), and poor supervision was also associated with unsafe action (OR = 3.429, 95% CI: 1.194–9.848) (Afifah et al., 2025). Murti and Inayah (2025) similarly reported that failed safety induction among Indonesian energy-sector operational and maintenance workers was associated with unsafe behavior (OR 2.549, $p = .013$). These observational results do not prove that training alone causes safer behavior, but they identify modifiable learning and supervisory targets.

Active safety training has a plausible advantage because it requires rehearsal, feedback, and application rather than passive receipt of information. Earlier evidence showed that more engaging worker-safety training methods generally produced larger gains in knowledge and safer performance (Burke et al., 2006), while a systematic review found stronger evidence for improvement in worker OHS behavior than for downstream health outcomes (Robson et al., 2012). More recent reviews of virtual reality (VR) safety training have reported benefits for knowledge acquisition, retention, hazard recognition, and selected behavior-related outcomes across high-risk sectors, but have also emphasized short follow-up, heterogeneous outcome measures, and the scarcity of organizational-level outcomes (Toyoda et al., 2022; Stefan et al., 2023; Scorgie et al., 2024; Man et al., 2024; Strojny & Dużmańska-Misiarczyk, 2023).

Indonesian evidence directly involving electrical workers is emerging. Pribadi et al. (2024) evaluated OSH learning among 50 electrical-sector technical-support workers using two intervention sequences containing conventional instruction and VR. Knowledge improved significantly in both sequences, with particularly large first-stage gains in the VR-first group. Indonesian literature has also described VR as a promising workplace-safety training modality (Pribadi et al., 2023). International studies extend this evidence to electrical distribution, low-voltage electrical safety, utilities, construction, cranes, mining, and other high-risk work (Sacks et al., 2013; Gallagher et al., 2020; Jeelani et al., 2020; Nykänen et al., 2020; Bracco et al., 2021; Dhalmahapatra et al., 2021; Han et al., 2022; Yu et al., 2022; Abbas et al., 2023; Rey-Becerra et al., 2023; Stefan et al., 2024; Pireddu et al., 2025).

Two distinct gaps therefore motivate this review. The empirical gap is the absence of a controlled Indonesian power-plant maintenance trial in which simulation-based training is followed by objective measurement of field unsafe-action frequency. The methodological and evidentiary gap arises because the relevant evidence is distributed across different populations, study designs, intervention formats, and outcome levels; consequently, evidence that simulation improves knowledge or task performance cannot be treated as equivalent to evidence that it reduces field unsafe actions or accidents. The present search did not identify a previous integrative review that specifically combined evidence from Indonesian power-plant, energy, and electrical sectors with

international evidence on simulation-based safety training evidence while explicitly separating proximal learning outcomes from field unsafe-action outcomes. An integrative review is appropriate because it permits structured synthesis across experimental and non-experimental evidence while retaining attention to methodological differences (Whittemore & Knafl, 2005). The objective of this study is therefore to synthesize and critically appraise available evidence relevant to simulation-based safety training and unsafe-action prevention in the Indonesian power-plant maintenance context. The review asks: what does the current evidence indicate about (1) unsafe-action determinants in relevant Indonesian workers, (2) simulation/VR effects on proximal learning and performance outcomes, and (3) the degree to which international intervention evidence can reasonably inform, but not substitute for, direct Indonesian field evidence?

METHODS

1. Study Design

This study used an integrative review approach based on the framework described by Whittemore and Knafl (2005): problem identification, literature search, data evaluation, data analysis, and presentation. The design was selected because the question requires integration of heterogeneous evidence, including Indonesian cross-sectional studies that identify unsafe-action determinants, Indonesian quasi-experimental learning evidence, international simulation interventions, and systematic reviews used as higher-level triangulation. PRISMA 2020 principles were used only as reporting aids for search and study-selection transparency and should not be interpreted as a claim that this article is a registered or exhaustive systematic review. It is not presented as a new primary intervention study, and no worker observations, questionnaires, or company accident records were generated for this manuscript. It is also not presented as a *de novo* meta-analysis because the included populations, interventions, comparators, designs, and outcomes were not sufficiently homogeneous for a defensible pooled effect estimate.

2. Information Sources and Search Date

Searches used PubMed/MEDLINE, ScienceDirect, the Directory of Open Access Journals (DOAJ), and Indonesian journal portals, supplemented by backward citation searching from eligible articles and major reviews. The exact date and source-specific record counts of the earliest search were not preserved in the original database-export logs. For this revision, each named source and the citation chain were rechecked on 10 September 2026. Because the historical numbers of records retrieved, duplicates removed, records screened by title and abstract, full texts assessed, and studies excluded cannot be reliably reconstructed, these numbers are reported as not recoverable (NR) rather than estimated. Table 1 documents the available search record. Figure 1 uses an adapted PRISMA 2020-style flow to show the selection process and the final analytic set while explicitly identifying unavailable historical denominators. This preserves transparency without implying that the review was an exhaustive systematic review.



Table 1. Search Record and Documentation Status

Source	Initial search date	Verification date	Documentation status	Record count
PubMed/MEDLINE	Exact date NR	10 Sep 2026	Source rechecked using reported concept blocks; bibliographic details verified where relevant.	Historical n NR
ScienceDirect	Exact date NR	10 Sep 2026	Source rechecked; article title/abstract/keyword search logic adapted to platform syntax.	Historical n NR
DOAJ	Exact date NR	10 Sep 2026	Source rechecked using keyword/phrase logic in the platform search interface.	Historical n NR
Indonesian journal portals	Exact date NR	10 Sep 2026	English and Indonesian equivalents used through native portal search interfaces; title/DOI records verified when available.	Historical n NR
Backward citation searching	Exact date NR	10 Sep 2026	Reference lists of eligible studies and major reviews checked for additional relevant evidence.	Historical n NR
Final core analytic set	N/A	10 Sep 2026	Eligibility and relevance assessment completed for the retained core evidence.	12 studies (3 Indonesian; 9 international)

Note. NR = not recoverable from the original search logs. No retrospective record counts were imputed.

3. Search Strategy

Two concept blocks were used and adapted to database syntax. The context-focused string was: ("unsafe action" OR "unsafe behavior" OR "unsafe act") AND ("simulation-based training" OR simulation OR "virtual reality" OR VR) AND ("power plant" OR electricity OR electrical OR utility OR maintenance) AND (Indonesia OR worker* OR occupational). A broader intervention string was: ("simulation-based training" OR "virtual reality" OR VR) AND (safety OR occupational) AND (electrical OR utility OR construction OR industrial) AND (training OR "hazard recognition" OR behavior OR performance). The same conceptual blocks were retained across sources, but operators and field restrictions were adapted to the native interface. The original records do not document a separate controlled-vocabulary/MeSH expansion; therefore, use of MeSH is not claimed. Quotation marks were used for multiword phrases where supported, and truncation was limited to worker* where the platform supported it. Indonesian equivalents were used in national portals. Exact titles and DOIs were verified on publisher or indexing pages, and citation chaining was used to identify influential comparative studies and reviews not captured by the context-focused string. Table 2 documents the database-specific implementation reported for reproducibility.

Table 2. Database-Specific Search Strategy and Field Adaptation

Database/source	Documented implementation for the revised method
PubMed/MEDLINE	Core Boolean phrases were searched as keywords/phrases, with title/abstract field restriction specified for reproducibility where supported. Reported core terms: unsafe actions/behavior/act; simulation-based training/simulation/virtual reality/VR; power plant/electricity/electrical/utility/maintenance; Indonesia/worker*/occupational. No separate MeSH expansion is claimed because MeSH use was not documented in the original search log. Truncation: worker*.
ScienceDirect	The same concept blocks were adapted to ScienceDirect Boolean syntax and searched in article bibliographic text (title/abstract/keywords as supported by the interface). Phrase quotation marks were retained where supported; worker* was the only reported truncation term.
DOAJ	The same concept blocks were used as keyword/phrase searches through the DOAJ interface, with Boolean operators and phrase quotation adapted to platform syntax. No controlled-vocabulary expansion was used or claimed.
Indonesian journal portals	English terms were paired with Indonesian equivalents, including tindakan/perilaku tidak aman, keselamatan dan kesehatan kerja/K3, simulasi/virtual reality, pembangkit listrik/listrik/energi, and pemeliharaan. Native portal fields were used because field-tag syntax was not uniform across portals.
Backward citation searching	Reference lists of eligible primary studies and major reviews were checked for studies matching the eligibility criteria; title/DOI records were then verified on publisher or indexing pages.

4. Eligibility Criteria

Studies were eligible for the analytic synthesis when they were peer-reviewed journal articles published from 2013 through 10 September 2026; written in English or Indonesian; examined adult workers, technical personnel, or directly relevant safety trainees; and provided extractable evidence on unsafe actions/unsafe behavior, OSH knowledge, hazard recognition, procedural performance, safety behavior, task errors, or incident-related outcomes. Indonesian studies were included when they addressed power-plant/energy/electrical workers or directly relevant unsafe-action determinants. International construction, mining, utility, electrical, and other high-risk industrial studies were included only when they offered a plausible transfer pathway to power-plant maintenance through at least one of the following: comparable high-energy or hazardous work, procedural safety decisions, hazard-recognition demands, PPE or isolation/permit-related competencies, simulation/VR or proficiency-based training, or safety-behavior/task-performance outcomes. Transferability was judged qualitatively from (1) task and hazard similarity, (2) worker/technical population similarity, (3) intervention similarity, (4) proximity of the measured outcome to field behavior, and (5) contextual distance from power-plant maintenance. Evidence



from more distant sectors was used to inform mechanisms and training design, not as a direct estimate of effect in Indonesian power plants. Systematic reviews/meta-analyses were retained only as higher-level triangulation evidence and were not numerically combined with overlapping primary studies. Studies were excluded if they were non-peer-reviewed, purely conceptual or technical-development papers without a learning/safety outcome, medical or military simulations, student-only studies without clear relevance to occupational safety, or reports lacking sufficient methods/outcome information.

5. Study Selection and Scope

Eligibility was assessed at title/abstract and then full-text or publisher-record level by a single reviewer. The final analytic synthesis included 12 peer-reviewed core studies: three Indonesian studies (Afifah et al., 2025; Murti & Inayah, 2025; Pribadi et al., 2024) and nine international sources selected for intervention relevance, design strength, or synthesis value (Gallagher et al., 2020; Nykänen et al., 2020; Jeelani et al., 2020; Bracco et al., 2021; Sacks et al., 2013; Rey-Becerra et al., 2023; Stefan et al., 2024; Man et al., 2024; Scorgie et al., 2024). Additional publications were used for background, methodological context, or triangulation but were not treated as independent core evidence in the analytic table. Full-text exclusion reasons were: non-peer-reviewed publication; technical/conceptual development without a learning or safety outcome; medical or military simulation; student-only evidence without clear occupational relevance; or insufficient methods/outcome information. Historical numbers identified, deduplicated, screened, excluded, and assessed at full text are not recoverable from the original logs and therefore are not imputed. Study selection and methodological appraisal were performed by a single reviewer, which may introduce selection and appraisal bias. The adapted PRISMA-style flow in Figure 1 reflects these documented features and the final included set.

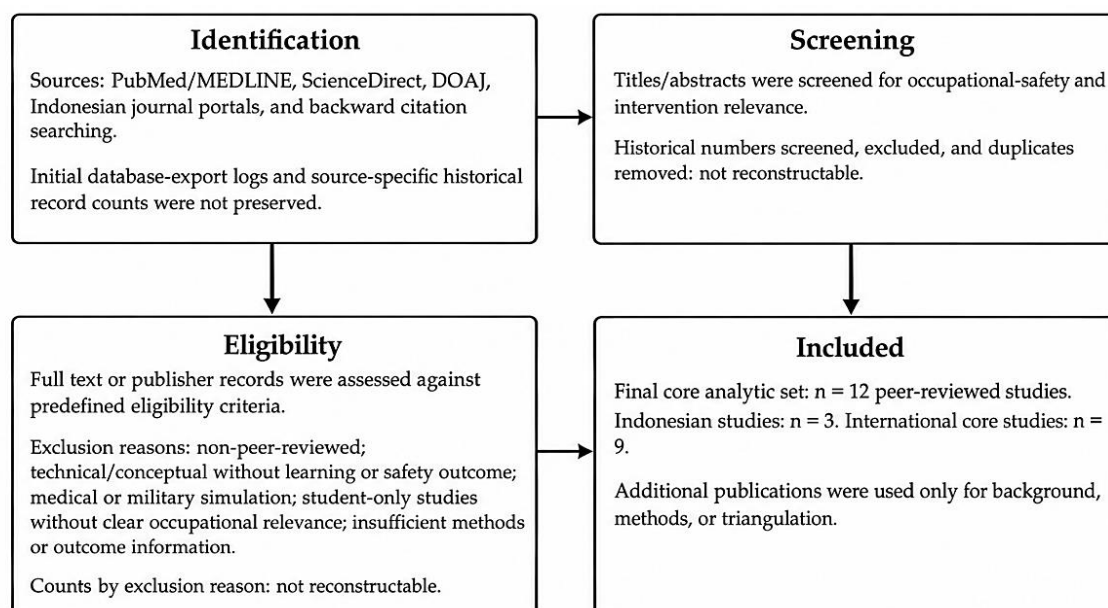


Figure 1. Adapted PRISMA 2020-Style Flow for the Integrative Review. Historical Identification, Duplicate-Removal, Screening, and Exclusion Counts Are Reported as Not Recoverable Rather Than Estimated; the Final Core Analytic Set Comprised 12 Studies

6. Data Extraction

A predefined extraction matrix was used to record author/year, country and sector, sample, study design, intervention/comparator, outcome domain, key quantitative or structured findings, follow-up interval, major limitations, and relevance/transferability to Indonesian power-plant maintenance. Outcomes were grouped a priori into four domains: (1) contextual determinants of unsafe action; (2) learning/knowledge and hazard recognition; (3) task performance or safety behavior; and (4) distal field outcomes such as unsafe-action frequency, utility strikes, near misses, or incidents. Percentage change was calculated only when the source supplied compatible pre/post scores; otherwise, published statistics were reported without re-analysis. The complete study-level extraction matrix is provided as Supplementary Table S1.

7. Methodological Quality and Evidence Weighting

Design-appropriate JBI critical-appraisal criteria were applied to the core studies, including analytical cross-sectional, quasi-experimental, randomized trial, and systematic-review tools (Aromataris et al., 2015; Barker et al., 2023; Barker et al., 2024; Barker et al., 2026). Because this is a single-author integrative review, appraisal was performed by the author and used for interpretive weighting rather than as a numerical exclusion threshold. Table 3 reports the JBI-relevant strengths, unclear/partial domains, and design-specific concerns that explain the Moderate or High interpretive weighting assigned to each core study. "Unclear" was used when the information available to the review did not support a definite judgment. Higher interpretive weight was assigned when design safeguards were stronger, outcomes were objectively measured, follow-up captured behavior rather than only reaction/knowledge, and the population/task was closer to power-plant maintenance. These categories are narrative confidence judgments for this integrative review, not GRADE ratings.

Table 3. JBI-Informed Critical Appraisal Results and Rationale for Interpretive Weighting

Study / design-specific JBI tool	JBI-relevant strengths clearly supported	Partial/unclear domains or design-specific concerns	Interpretive weighting
Afifah et al. (2025) / analytical cross-sectional	Clearly defined worker context; quantitative associations and regression estimates reported.	Cross-sectional temporality; representativeness and residual confounding cannot be fully resolved from the extracted report; no intervention follow-up.	Moderate
Murti & Inayah (2025) / analytical cross-sectional	Defined energy-sector worker sample; association between induction status and unsafe behavior reported.	Cross-sectional design; temporal ordering and residual confounding remain uncertain; no post-intervention behavioral follow-up.	Moderate



Study / design-specific JBI tool	JBI-relevant strengths clearly supported	Partial/unclear domains or design-specific concerns	Interpretive weighting
Pribadi et al. (2024) / quasi-experimental	Structured intervention sequences; repeated knowledge measurement; statistically significant within-sequence learning change.	Crossover/sequence design does not provide a simple parallel-group causal estimate; primary outcome is learning rather than field unsafe action.	Moderate
Gallagher et al. (2020) / randomized trial	Prospective randomized and blinded comparison; objectively assessed task errors; subsequent field utility-strike outcome.	Field implementation phase is not equivalent to the randomized comparison; task/sector differs from power-plant maintenance.	High
Nykänen et al. (2020) / randomized trial	Randomized controlled design; comparator training; one-month follow-up; multiple safety-competency outcomes.	Longer-term safety performance included self-report and is context-specific to construction; VR delivery/technical factors may influence response.	High
Jeelani et al. (2020) / quasi-experimental before-after	Structured immersive training; hazard-recognition and hazard-management outcomes directly measured.	Before-after design without randomized concurrent control in the extracted evidence; long-term transfer to field behavior not established.	Moderate
Bracco et al. (2021) / quasi-experimental/developmental evaluation	High-fidelity electricity-work simulation; procedure-compliance and stress-related indicators considered.	Development/evaluation design; limited causal control; long-term and field accident outcomes not established.	Moderate
Sacks et al. (2013) / comparative intervention	VR and conventional training compared; pre/post learning and one-month recall assessed; task-specific effects reported.	Effects varied across tasks; field unsafe-action or incident outcomes were not the primary endpoint; allocation safeguards are less explicit in the extracted evidence.	Moderate
Rey-Becerra et al. (2023) / quasi-experimental non-equivalent groups	Comparator training; short- and longer-term outcome assessment; multiple safety-related domains measured.	Non-equivalent groups; longer-term outcomes include self-report; no direct power-plant task match.	Moderate

Study / design-specific JBI tool	JBI-relevant strengths clearly supported	Partial/unclear domains or design-specific concerns	Interpr etive weight ing
Stefan et al. (2024) / within-group experiment	Pre-, immediate post-, and four-week knowledge assessment; retention assessed.	Small sample (n=18); no concurrent control group; outcome is learning/retention rather than field behavior.	Moder ate
Man et al. (2024) / systematic review and meta-analysis	Systematic synthesis with meta-analysis; multiple outcome categories and moderator analysis. Broad multi-industry	Substantial cross-study heterogeneity and construction-sector focus limit direct transfer to Indonesian power plants. Heterogeneous	High
Scorgie et al. (2024) / systematic review and meta-analysis	systematic review; meta-analytic comparison of knowledge acquisition and retention.	interventions/outcomes; long-term retention was measured in only a minority of included studies.	High

8. Synthesis

No pooled meta-analysis was performed because the included studies differed materially in population, sector, intervention format, comparator, design, follow-up, and outcome level. Heterogeneous findings were therefore compared using a constant-comparison approach consistent with integrative-review methodology: similarities, differences, moderators, outcome level, and transferability to the Indonesian target context were examined. Causal language was reserved for randomized or controlled intervention evidence in the populations actually studied. Indonesian observational data were used to identify contextual risk factors, not to claim that simulation caused a reduction in unsafe action.

RESULTS

The 12 core studies formed a deliberately heterogeneous evidence set. The Indonesian studies defined the local problem and modifiable determinants; the international intervention studies tested simulation or VR against conventional training or against baseline; and two systematic reviews summarized broader patterns. Accordingly, the results below are not a pooled estimate of intervention effectiveness and should not be read as a single causal effect for Indonesian power-plant maintenance workers.

Table 4. Core Studies Included in the Integrative Review

Study	Population / Setting	Design	Key Finding	Outcome Relevance	Weight
Afifah et al. (2025)	Indonesia; power-plant repair workers; n = 69	Cross-sectional	62.32% reported high unsafe action; low OSH knowledge (OR =	Contextual determinants	Moderate



			4.200) and poor supervision (OR = 3.429) were associated with unsafe actions.		
Murti & Inayah (2025)	Indonesia; energy operations and maintenance workers; n = 148	Cross-sectional	35.8% reported unsafe behavior; failed safety induction was associated with unsafe behavior (OR = 2.549, p = .013).	Training-related determinant	Moderate
Pribadi et al. (2024)	Indonesia; electrical technical-support workers; n = 50	Quasi-experimental crossover	Knowledge increased in both sequences; in the VR-first sequence, scores increased from 11.96 to 19.16 after the first intervention (p < .001).	Learning and knowledge	Moderate
Gallagher et al. (2020)	Utility workers	Prospective randomized, blinded study	33% fewer objectively assessed task errors; utility strikes decreased by 35–61% after implementation.	Task errors and field incidents	High
Nykänen et al. (2020)	Finland; construction workers; n = 119	Randomized controlled trial	VR improved safety motivation, self-efficacy, and outcome expectancies, with greater self-reported safety performance at one month.	Behavior-related competencies	High
Jeelani et al. (2020)	Construction trainees/workers; n = 53	Before–after intervention	Hazard recognition improved by 39%,	Hazard recognition	Moderate



			and hazard management improved by 44%.	and management	
Bracco et al. (2021)	Electricity distribution workers	High-fidelity simulation development and evaluation	Participants evaluated the simulation positively; compliant behavior patterns were associated with lower stress indicators. Long-term effects were not established.	Simulation process and compliance	Moderate
Sacks et al. (2013)	Construction trainees; n = 66	Comparative intervention	VR showed advantages in selected task domains and retention, but not across all general-site safety outcomes.	Knowledge and recall	Moderate
Rey-Becerra et al. (2023)	Colombia; construction workers; n = 102	Quasi-experimental non-equivalent groups	VR improved short-term knowledge and attitudes; no long-term differences were found in risk perception, self-reported behavior, or safety climate.	Short- versus long-term outcomes	Moderate
Stefan et al. (2024)	Low-voltage electrical safety participants; n = 18	Within-group experiment	Knowledge improved immediately and remained above baseline after four weeks; however, the sample was small and uncontrolled.	Knowledge and retention	Moderate



Man et al. (2024)	12 studies; 65 records	Systematic review and meta-analysis	VR favored behavioral, skill-based, and experiential outcomes; effects were moderated by training context and work experience.	Higher-level synthesis	High
Scorgie et al. (2024)	52 VR safety-training articles	Systematic review and meta-analysis	VR favored knowledge acquisition and retention; only 36% of reviewed studies measured retention.	Higher-level synthesis	High

Note: OSH = occupational safety and health; VR = virtual reality; OR = odds ratio. The evidence weight follows the classification provided in the original review material.

1. Indonesian Evidence on Unsafe Actions and Training-Related Determinants

Afifah et al. (2025) provide the most direct contextual evidence for the target workforce. Among 69 engineering-supporting workers involved in mechanical, electrical, control, and instrumentation activities for power-plant repair services, 43 workers (62.32%) were categorized as having high unsafe-action levels and 26 (37.68%) as low. Thirty-six workers (52.17%) had low OSH knowledge and 31 (44.93%) rated OSH supervision as poor. OSH supervision was associated with unsafe action ($p=.019$), as was OSH knowledge ($p=.006$). In binary logistic regression, poor supervision was associated with 3.429-fold higher odds of unsafe action (95% CI 1.194-9.848) and low OSH knowledge with 4.200-fold higher odds (95% CI 1.481-11.913). Reported unsafe practices included grinding without a protective cover, lifting without a tagline, and incorrect PPE use during welding.

Murti and Inayah (2025) add an energy-sector training-system perspective. Among 148 operational and maintenance workers, 35.8% were categorized as showing unsafe behavior, and failure to pass safety induction was associated with unsafe behavior (OR 2.549, $p=.013$). Because both Indonesian studies are observational, the associations cannot establish that changing knowledge, supervision, or induction alone will cause a corresponding reduction in field unsafe action. Their value is contextual: they identify targets that can be addressed and then tested in an intervention trial.

2. Indonesian Evidence on Simulation/VR

Pribadi et al. (2024) provide the strongest Indonesian evidence that VR-containing OSH learning can improve a proximal outcome among electrical workers. Fifty technical-support workers were allocated to two intervention sequences: conventional instruction followed by VR, or VR

followed by conventional instruction. Group A increased from a mean knowledge score of 13.00 (SD 2.63) to 16.80 (SD 2.44) after the first intervention and 19.96 (SD 2.70) after the second. Group B increased from 11.96 (SD 2.47) to 19.16 (SD 2.82) after VR as the first intervention and 19.20 (SD 3.09) after the second. Both first-stage changes were statistically significant ($p < .001$). The sequence design supports a learning benefit but does not provide a direct estimate of field unsafe-action reduction; it also makes a simple parallel-group causal comparison inappropriate.

The distinction between knowledge and behavior is important. VR may improve the worker's ability to identify PPE, electrical hazards, isolation steps, or procedural choices, yet actual maintenance behavior remains influenced by time pressure, supervision, permit-to-work controls, equipment condition, staffing, and organizational norms. Therefore, the Indonesian VR study supports feasibility and learning transfer potential, not a quantified reduction in unsafe actions at power plants.

3. International Experimental and Review Evidence

International intervention evidence is strongest for proximal learning and task-performance outcomes. Gallagher et al. (2020) found 33% fewer objectively assessed performance errors after proficiency-based progression simulation compared with standard training ($p = .006$); after division-wide implementation, utility strikes decreased by 35-61% ($p = .028$). This is important because the outcomes extended beyond knowledge, but the tasks involved buried-utility location/excavation rather than Indonesian power-plant maintenance. Nykänen et al. (2020), in a randomized trial of 119 construction workers, found stronger effects of immersive VR than lecture-based training on safety motivation, self-efficacy, outcome expectancies, and self-reported safety performance at one month, while emphasizing that VR should complement rather than replace other safety methods.

Other studies show both benefits and boundaries. Jeelani et al. (2020) reported 39% improvement in hazard recognition and 44% improvement in hazard management after a virtual-environment training protocol. Sacks et al. (2013) found that VR's advantage was task-dependent: significant benefits were observed for selected construction activities and retention, but not uniformly for general site safety. Stefan et al. (2024) found significant immediate learning gains in 18 participants and retention above baseline four weeks later, but the uncontrolled small sample limits causal certainty. Bracco et al. (2021) showed that high-fidelity simulation can support reflection and procedure-compliant behavior among electricity distribution workers, but explicitly called for assessment of longer-term effects.

The most important counterpoint comes from Rey-Becerra et al. (2023). Among 102 construction workers, VR-based work-at-height training produced higher short-term knowledge and attitudes than lecture training, but the groups did not differ on longer-term risk perception, self-reported behavior, or safety climate. This finding demonstrates why improvement in reaction or learning cannot automatically be translated into claims about sustained behavior. Similar concerns appear in methodological reviews: Stefan et al. (2023) found that VR safety studies overwhelmingly evaluate reaction and learning rather than behavior and organizational results, and Scorgie et al. (2024) reported that only 36% of reviewed studies included retention measurements.

Meta-analytic evidence is therefore supportive but not uniform. Man et al. (2024) found advantages of VR over traditional construction-safety training for behavior, skills, and experience



outcomes and identified training context and workers' experience as significant moderators. Scorgie et al. (2024) similarly concluded that VR safety training generally outperforms traditional methods for knowledge acquisition and retention across multiple sectors. These syntheses strengthen the case for simulation as an active-learning strategy, while simultaneously showing that effect size depends on outcome definition, trainee experience, scenario design, and follow-up.

4. Integrated Interpretation of the Strength and Transferability of Evidence

Taken together, the evidence supports three different propositions with different confidence. First, confidence is moderate-to-high that well-designed simulation/VR can improve proximal outcomes such as knowledge, hazard recognition, engagement, self-efficacy, and selected task performance in high-risk work. This conclusion is supported by randomized, quasi-experimental, and meta-analytic evidence. Second, confidence is moderate that simulation can influence safety-related behavior under controlled or task-specific conditions, but the evidence is less consistent at longer follow-up and often relies on self-report. Third, confidence is low for the specific causal claim that simulation reduces the frequency of unsafe actions among Indonesian power-plant maintenance workers, because no included Indonesian study directly tested that outcome after simulation training.

This distinction is the central result of the synthesis. The Indonesian data establish a relevant unsafe-action burden and identify knowledge, supervision, and induction as modifiable factors. International studies show that simulation can improve several competencies that plausibly contribute to safer work. However, bridging those two evidence streams requires an explicit transfer assumption. The evidence justifies testing and implementing simulation as an evidence-informed component of a broader safety system; it does not justify attributing a precise percentage reduction in Indonesian power-plant unsafe actions to simulation on the basis of current secondary evidence.

Table 5. Evidence-Weighting Framework Used for Interpretation

Evidence question	Best available evidence	Confidence for this review	Interpretive implication
Is unsafe action a relevant problem in Indonesian power/energy maintenance?	Indonesian cross-sectional studies with quantitative associations	Moderate	Problem and determinants are well supported; causality is not.
Can simulation/VR improve safety knowledge and hazard recognition?	RCTs/quasi-experiments plus systematic reviews/meta-analyses	Moderate-High	Evidence supports improvement in proximal learning outcomes.
Can simulation improve task performance or safety behavior?	Utility RCT plus construction RCT/quasi-experiments	Moderate	Benefits occur, but are task-, context-, and follow-up-dependent.

Evidence question	Best available evidence	Confidence for this review	Interpretive implication
Does simulation reduce field unsafe-action frequency in Indonesian power plants?	No direct Indonesian controlled field trial identified	Low / insufficient direct evidence	Do not claim a causal percentage reduction; conduct field trial.

DISCUSSION

The synthesis supports simulation-based safety training as an evidence-informed strategy for competencies that are relevant to unsafe-action prevention, but the evidence is not equivalent across outcome levels. Agreement across studies is strongest for active learning: VR or simulation commonly improves knowledge, hazard recognition, engagement, confidence, or task performance relative to passive instruction or baseline. This pattern is consistent with older safety-training evidence showing that greater learner engagement and practice are associated with stronger training outcomes (Burke et al., 2006) and with contemporary cross-sector VR reviews (Toyoda et al., 2022; Stefan et al., 2023; Scorgie et al., 2024).

The studies do not, however, show that VR is universally superior. Sacks et al. (2013) found that the advantage varied by construction task. Rey-Becerra et al. (2023) found short-term gains in knowledge and attitudes without corresponding long-term group differences in risk perception, self-reported behavior, or safety climate. Stefan et al. (2024) documented retention above baseline but also a decline from immediate post-training performance. These differences are not contradictory; they indicate that learning acquisition, retention, behavior transfer, and organizational outcomes are separate stages. Reviews of virtual training likewise show an imbalance toward reaction and learning measures and much weaker evidence for behavior and results (Strojny & Dużmańska-Misiarczyk, 2023; Stefan et al., 2023).

Worker experience and training design also modify outcomes. Man et al. (2024) identified training context and mean work experience as moderators, while Yu et al. (2022) directly compared novice and experienced construction workers across hazardous scenarios. Studies of simulator fidelity and user experience show that greater realism can improve presence and usability, but high presence alone does not guarantee behavior change (Abbas et al., 2023; Luo et al., 2023; Yoo et al., 2023). Industrial studies of cranes, mining, and other hazards similarly suggest that scenario relevance, feedback, and opportunity for repeated practice are central to the value of VR (Dhalmahapatra et al., 2021; Pireddu et al., 2025; Al-Hamad & Gilányi, 2025).

For Indonesian power-plant maintenance, simulation should therefore be designed around actual critical tasks and observed unsafe actions rather than generic safety content. Relevant scenarios include lockout/tagout and verification of zero energy, permit-to-work checks, hot work, grinding and guarding, lifting/tagline use, work at height, confined-space entry, rotating equipment isolation, electrical boundaries, PPE selection, stop-work decisions, and supervisor communication. High-fidelity physical simulation may be preferable where tactile equipment handling is essential, while immersive VR may be particularly useful for hazard recognition, rare-event rehearsal, spatial decision-making, and standardized repeat practice. The choice should be driven by learning objectives rather than technology novelty.



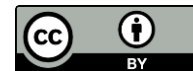
The Indonesian observational evidence also explains why simulation alone is unlikely to be sufficient. Afifah et al. (2025) found independent associations of knowledge and supervision with unsafe action, while Murti and Inayah (2025) linked failed safety induction with unsafe behavior. A worker may perform correctly in a simulation but revert to unsafe practice if field supervision is weak, production pressure dominates, permit controls are bypassed, or equipment conditions differ from the training scenario. This is consistent with Robson et al. (2012), who found stronger evidence for training effects on behavior than on downstream health outcomes and cautioned against expecting training alone to produce large changes in injury outcomes.

A more defensible implementation model is therefore blended and competency-based. Simulation should complement safety induction, toolbox/safety talks, permit-to-work systems, engineering controls, PPE programs, supervisor coaching, and field observation. Workers should be required to demonstrate critical actions to a defined proficiency threshold, receive structured debriefing, repeat deficient steps, and then undergo workplace follow-up. This approach aligns with proficiency-based progression evidence from utility work (Gallagher et al., 2020) and with simulation designs emphasizing observation, debriefing, and reflective learning (Bracco et al., 2021).

Evaluation should deliberately separate proximal and distal outcomes. Proximal measures may include knowledge, hazard recognition, procedural accuracy, correct PPE selection, isolation verification, stop-work decisions, communication, and checklist adherence. Distal measures should include observed unsafe actions per 1,000 work observations, repeat permit deviations, near misses, equipment damage, utility strikes or comparable events, and incident frequency. Baseline, immediate post-training, and follow-up at one and three months would allow assessment of acquisition and transfer. Independent or blinded observers should be used where feasible, and behavior definitions should be standardized before data collection.

The present evidence base has important limitations. The core Indonesian power-plant study is cross-sectional and cannot establish intervention effects. The Indonesian VR study mainly demonstrates learning change, not field behavior. International intervention studies involve different industries, regulations, tasks, worker experience, and technologies. Some studies have small samples or lack control groups. Systematic reviews report substantial heterogeneity and a predominance of short-term outcomes. In addition, this integrative review is a structured targeted synthesis rather than an exhaustive registered systematic review; the original draft did not preserve historical database-export logs, so source-specific identification counts, duplicate counts, screening denominators, and full-text exclusion counts could not be reconstructed and were not imputed. Study selection and methodological appraisal were performed by a single reviewer, which may introduce selection and appraisal bias. These limitations require conservative causal language.

Future research should conduct a controlled Indonesian field trial among power-plant maintenance or overhaul workers. A cluster-randomized or stepped-wedge design could compare conventional induction with simulation-enhanced competency training while preserving operational practicality. The primary outcome should be objectively observed unsafe-action frequency, supported by secondary outcomes such as knowledge, hazard recognition, procedural performance, near misses, and permit deviations. A sample-size calculation, pre-specified analysis plan, assessor training, and follow-up beyond the immediate post-test would materially strengthen



the evidence. Such a study would directly test the transfer assumption that currently links Indonesian risk-factor evidence with international simulation evidence.

CONCLUSIONS

This integrative review shows that unsafe actions are a material safety concern in Indonesian power-plant repair and energy-maintenance contexts and are associated with modifiable factors including OSH knowledge, supervision, and safety induction. Indonesian electrical-worker evidence also shows that VR-containing training can produce substantial short-term knowledge gains. International randomized, quasi-experimental, and review evidence generally supports simulation/VR for improving proximal learning outcomes and selected task or behavior measures.

The evidence does not establish that simulation-based training directly reduces unsafe-action frequency among Indonesian power-plant maintenance workers, nor does it support a precise causal percentage reduction for that population. The most defensible conclusion is that simulation is a plausible, evidence-informed component of a broader competency and safety-management system. Organizations may integrate realistic scenario practice with safety induction, permit-to-work controls, supervisor coaching, debriefing, repeat practice, and competency verification while collecting field behavior data. Direct controlled Indonesian trials with objective unsafe-action outcomes are required before stronger causal claims are made.

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