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# Implementation of Drone-Based Monitoring for Work at Height Operations in the Petrochemical Industry: A Case Study at PT XYZ

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***Abstract***

***Introduction:*** *Work-at-height activities in the petrochemical industry involve significant occupational safety risks due to PPE non-compliance, unsafe behavior, and limitations of conventional monitoring systems.* ***Objective:*** *This study aimed to evaluate the effectiveness of drone-based safety monitoring in improving Full Body Harness compliance, reducing unsafe behavior, and decreasing occupational risks during work-at-height activities.* ***Method:*** *A field-based quasi-experimental pre-test-post-test design was conducted over four months using structured observations, drone-based visual documentation, paired-sample t-test, Cohen's d effect size, and Fine-Kinney risk assessment.* ***Result and Discussion:*** *Drone implementation reduced Full Body Harness violations from 23 to 9 cases (60.87% reduction) and unsafe behavior from 12 to 6 cases (50% reduction). Statistical analysis confirmed significant improvements in PPE compliance (p = 0.004; Cohen's d = 1.50) and unsafe behavior (p = 0.020; Cohen's d = 1.06). Fine-Kinney assessment showed that monitoring risks decreased from 900 (Very High Risk) to 18 (Acceptable Risk) for elevated structure observation and from 540 (Very High Risk) to 30 (Possible Risk) for lifting operations.* ***Conclusions:*** *Drone-based safety monitoring effectively improves safety behavior, enhances monitoring effectiveness, and reduces occupational risks during work-at-height activities in the petrochemical industry.*

## Introduction

Work at height remains one of the most hazardous activities across industrial sectors and continues to contribute substantially to occupational fatalities despite ongoing improvements in occupational safety and health management systems. Recent statistics show that fatal workplace accidents caused by falls from height increased from 25% in 2021/2022 to 36% in 2023/2024 in the United Kingdom, while the United States reports falls as approximately 15% of all occupational fatalities (Health and Safety Executive, 2024). Occupational accidents generally result from the interaction of unsafe actions and unsafe working conditions rather than isolated human errors (Hossain *et al*., 2025). This perspective is consistent with the Swiss Cheese Model, which explains that accidents occur when multiple organizational defenses fail simultaneously, allowing latent organizational weaknesses to align with active human failures (Reason, 2000). In work at height operations, these failures commonly involve improper use of personal protective equipment (PPE), incorrect attachment of full body harnesses to anchor points, inadequate hazard identification, and insufficient supervision. Fatal incidents frequently occur during work on rooftops, scaffolding, ladders, floor openings, and elevated work platforms, emphasizing the importance of continuous monitoring throughout hazardous activities (Anantharaman *et al*., 2022).

Various preventive measures, including safety training, guardrails, personal fall arrest systems, and safety nets, have contributed to reducing fall-related accidents but largely function as passive controls after hazards have already emerged (Kodithuwakku Arachchige *et al*., 2021). Worker compliance with PPE requirements remains a persistent challenge because full body harnesses are often neglected due to discomfort, inconvenience, limited risk awareness, and established work habits (Borell *et al*., 2024). Non-compliance with personal fall arrest systems has consequently become one of the dominant contributing factors in fatal fall incidents (Putri *et al*., 2025). Conventional supervision based on periodic field inspections is also constrained by limited visibility, restricted monitoring coverage, and the inability to observe multiple work locations simultaneously. These limitations become increasingly significant in large industrial facilities where hazardous tasks are performed concurrently across different elevations.

These challenges are particularly critical in the petrochemical industry, where work at height is conducted within complex facilities containing hazardous chemicals, high-pressure systems, elevated structures, and, importantly, flammable or explosive atmospheres. The use of electronic equipment for monitoring must be carefully considered because ignition sources may create additional operational risks if they are not appropriately managed. At the same time, supervisors face considerable difficulty in observing multiple work locations because of restricted visibility and complex plant layouts. Conventional monitoring systems, such as fixed CCTV cameras, provide limited viewing angles and depend on permanent network infrastructure, reducing their effectiveness in dynamic industrial environments. Recent advances in Unmanned Aerial Vehicle (UAV) technology have created new opportunities to improve occupational safety monitoring by providing flexible visual access to elevated or hazardous locations while reducing direct exposure of inspectors to operational risks (Martinez *et al*., 2021). Compared with conventional inspection methods, drones also offer broader monitoring coverage and improve inspection efficiency, although many existing applications still rely on manual interpretation by operators, resulting in potential delays and subjective decision-making (Hossain *et al*., 2025).

Although UAV technology has attracted growing attention in occupational safety research, existing studies have mainly focused on construction projects, infrastructure inspection, or general UAV applications rather than work at height activities in petrochemical facilities. Hardjo *et al*. (2020) showed the effectiveness of drones for evaluating PPE compliance in construction projects, while Martinez *et al*. (2021) investigated UAV-based inspection systems for construction safety management. Gupta and Nair (2023) further concluded that UAVs have considerable potential for automated PPE detection and hazardous area monitoring, although technical challenges related to visual occlusion, lighting variability, and operational workflows remain unresolved. Rahmani and Weckman (2024) emphasized that the safety of drone operations is strongly influenced by pilot competence, human factors, and procedural compliance, showing the need for careful implementation in high-risk industrial environments. However, empirical evidence regarding drone-assisted monitoring for verifying full body harness usage and proper anchor point attachment during petrochemical work at height activities remains limited, particularly in Indonesia. Therefore, this study evaluates the implementation of drone-based monitoring to improve compliance with full body harness usage, reduce unsafe behaviors, and decrease occupational safety risks during work at height operations in the petrochemical industry.

## Method

This study employed a field quasi-experimental design to evaluate the effectiveness of drone-based safety monitoring in improving compliance with Full Body Harness (FBH) use, reducing unsafe behavior, and decreasing occupational risks associated with work at height in a petrochemical facility. A quasi-experimental approach was selected because the operational characteristics of the petrochemical industry do not permit the implementation of a fully randomized controlled trial without disrupting production activities or compromising occupational safety regulations. The intervention consisted of a single experimental factor, namely the safety monitoring method, which was implemented in two conditions: conventional manual supervision and drone-based monitoring. The research followed a pre-test-intervention-post-test framework in which baseline observations were conducted before drone implementation, followed by an intervention period and subsequent post-intervention assessment. Conducting the experiment under actual operating conditions was considered essential because workers' compliance with safety procedures cannot be realistically replicated in laboratory environments. Previous field investigations have similarly showed that real-world validation produces more reliable evidence regarding the practical effectiveness of drone-assisted safety inspection than simulated experiments (Martinez *et al*., 2021; Shanti *et al*., 2022). The research was conducted at PT XYZ, a representative Indonesian petrochemical company, over a four-month period from January to April 2026, covering preparation, baseline measurement, intervention implementation, post-intervention assessment, and statistical analysis.

The research variables were developed to enable objective measurement using structured observations supported by visual evidence collected from drone recordings. The independent variable was the occupational safety monitoring method, while monitoring effectiveness functioned as a process variable describing the capability of each monitoring approach to identify unsafe conditions and unsafe behaviors. Three dependent variables were subsequently evaluated, namely the reduction in occupational risk during work at height, the reduction in FBH violations, and the reduction in unsafe behavior after implementation of drone monitoring. Occupational risk levels were assessed using the Fine-Kinney Risk Assessment Method, whereas violations of PPE compliance and unsafe behavior were quantified through direct observations verified using photographs and video recordings. To minimize observer subjectivity, all observations were conducted using standardized inspection sheets accompanied by documentary evidence collected during both baseline and intervention phases. The operational definitions of all variables are showed in Table 1.

**Table 1**
Operational Definition

| Variable | Variable Type | Operational Definition | Measurement Output | Scale |
|---|---|---|---|---|
| Safety Monitoring Method | Independent (X) | Method used for supervising work at height | Conventional monitoring; Drone-based monitoring | Nominal |
| Monitoring Effectiveness | Process (M) | Capability of monitoring system to detect unsafe conditions | Observation coverage, unsafe act detection, monitoring accuracy | Interval |
| Reduction of Work-at-Height Risk | Dependent (Y1) | Reduction of occupational risk after intervention | Fine-Kinney risk score before and after intervention | Interval |
| Reduction of PPE Violations | Dependent (Y2) | Reduction in FBH non-compliance | Number/percentage of FBH violations | Ratio |
| Reduction of Unsafe Behavior | Dependent (Y3) | Reduction in unsafe behavior after intervention | Number of unsafe behaviors identified | Ratio |

Data collection relied on structured observation instruments specifically designed for occupational safety research in high-risk industrial environments. The primary instruments included observation sheets for FBH compliance, workplace inspection checklists, permit-to-work audit forms, incident and near-miss records, and visual documentation consisting of photographs and high-resolution drone videos. To ensure measurement quality, the instruments were developed according to the principles of validity, reliability, sensitivity, and practicality, thereby allowing consistent observations by different assessors throughout the experimental period. Drone operation was standardized using predefined technical specifications covering navigation systems, flight altitude, observation distance, and documentation procedures to ensure consistency during all monitoring sessions. The drone was operated solely as a passive observation platform without interfering with workers or production activities, while all captured images and videos were used exclusively to verify observational findings. Standardization was also applied to PPE compliance and unsafe behavior assessments so that every observation followed identical operational criteria, thereby reducing inter-observer variability. The technical specifications of the drone and the observational standards adopted in this study are showed in Tables 2-4.

**Table 2**
Drone Specifications and Operational Standards

| Parameter | Specification |
|---|---|
| Folded Dimensions | 204 × 106 × 72.6 mm |
| Diagonal Size | 372 mm |
| Weight | 768 g |
| Storage Media | Micro SD Card (up to 256 GB) |

| | |
|---|---|
| Hover Accuracy | ± 0.1 m (Vision), ± 0.5 m (GPS) |
| Maximum Flight Time | 35 min |
| Maximum Monitoring Height | 100 m |
| Maximum Observation Distance | 50 m from workers |
| Navigation System | GPS, GLONASS, BEIDOU |
| Main Function | Monitoring FBH compliance and unsafe behavior |
| Documentation | Photo and video evidence |

**Table 3**
Standardization of PPE (Full Body Harness) Violations

| Observation Criteria | Category |
|---|---|
| Worker wears Full Body Harness throughout work at height | Compliant |
| Worker does not wear Full Body Harness during work at height | Non-compliant |

**Table 4**
Standardization of Unsafe Behavior

| Observation Criteria | Category | Description |
|---|---|---|
| Lanyard properly attached to the designated anchor point | Safe Behavior | Worker is protected by the fall arrest system |
| Lanyard not attached to the designated anchor point | Unsafe Behavior | Worker is exposed to fall-from-height risk |

The intervention phase involved continuous deployment of drone-based monitoring during work-at-height activities, while the baseline period relied exclusively on conventional manual supervision. Before statistical analysis, data normality was examined using the Shapiro-Wilk test to determine the appropriate inferential procedure. Differences between pre-intervention and post-intervention measurements were analyzed using the paired-sample t-test for normally distributed data or the Wilcoxon signed-rank test for non-parametric data. The magnitude of intervention effectiveness was further evaluated using Cohen's d for parametric analysis or effect size (*r*) for non-parametric analysis, thereby providing quantitative evidence regarding the practical significance of drone implementation. Percentage reductions in FBH violations and unsafe behavior were calculated by comparing post-intervention values with baseline observations, while occupational risk reduction was determined using changes in Fine-Kinney scores. Occupational risk assessment was conducted using the Fine-Kinney Risk Assessment Method (Fine, 1971; Kinney & Wiruth, 1976), as showed in Table 5.

**Table 5**
Fine-Kinney Risk Assessment Rating Criteria and Risk Classification

| Parameter | Score | Description |
|---|---|---|
| Probability (Likelihood Level) | 10 | Highly likely |
| | 6 | Quite possible |
| | 3 | Unusual but possible |
| | 1 | Remotely possible |
| | 0.5 | Conceivable but very unlikely |
| | 0.2 | Practically impossible |
| | 0.1 | Virtually impossible |
| Exposure (Frequency of Exposure) | 10 | Continuous |
| | 6 | Frequent (daily) |
| | 3 | Occasional (weekly) |

| | | |
|---|---|---|
| | 2 | Infrequent (monthly) |
| | 1 | Rare (a few times a year) |
| | 0.5 | Very rare (yearly or less) |
| Consequence (Severity of Consequences) | 100 | Multiple fatalities |
| | 40 | Several fatalities |
| | 15 | Single fatality |
| | 7 | Severe injury / permanent disability |
| | 3 | Serious injury |
| | 1 | Minor injury |
| | 0.5 | First aid case |
| Risk Score Classification | > 400 | Very high risk |
| | 200-400 | High risk |
| | 70-200 | Substantial risk |
| | 20-70 | Possible risk |
| | < 20 | Acceptable risk |

To strengthen the credibility of the findings, quantitative results were triangulated using manual observations, drone-generated visual documentation, inspection records, and permit-to-work audits. Prior to implementation, all research procedures received formal approval from company management and the institutional ethics committee, while every participant provided informed consent and all personal information remained anonymous throughout the study in accordance with established principles of occupational safety research ethics.

## Result and Discussion

### 1. Result

A total of two observation phases were completed during this study to evaluate the effectiveness of drone-based safety monitoring for work-at-height activities in the petrochemical industry. The first phase reshowed the baseline condition during January-February 2026, in which all safety inspections were conducted using conventional manual supervision. The second phase was carried out during March-April 2026 following the implementation of drone-assisted monitoring under identical operational conditions. The comparison between these two observation periods enabled an objective assessment of changes in PPE compliance, unsafe behavior, and occupational risk. All observations were conducted using standardized inspection instruments, while every finding was verified through photographic or video documentation to ensure data consistency.

The baseline observations identified 35 occupational safety findings, indicating that work-at-height activities continued to present considerable safety challenges under conventional monitoring practices. Violations related to Full Body Harness (FBH) compliance reshowed the largest proportion of findings, accounting for 23 cases (66%), while unsafe behavior, primarily involving failure to connect the lanyard to the designated anchor point, accounted for 12 cases (34%). These findings suggest that improper PPE utilization remained the dominant safety issue during elevated work activities. Furthermore, repeated unsafe behaviors showed that conventional patrols and direct supervision were unable to continuously observe all work locations because of the extensive plant layout and limited visual accessibility. Consequently, unsafe practices could still occur between inspection intervals without being immediately detected by safety personnel.

**Table 6**
Baseline Safety Monitoring (January-February 2026)

| Type of Finding | Frequency | Percentage |
|---|---|---|
| PPE Violations | 23 | 66% |
| Unsafe Behavior | 12 | 34% |
| Total | 35 | 100% |

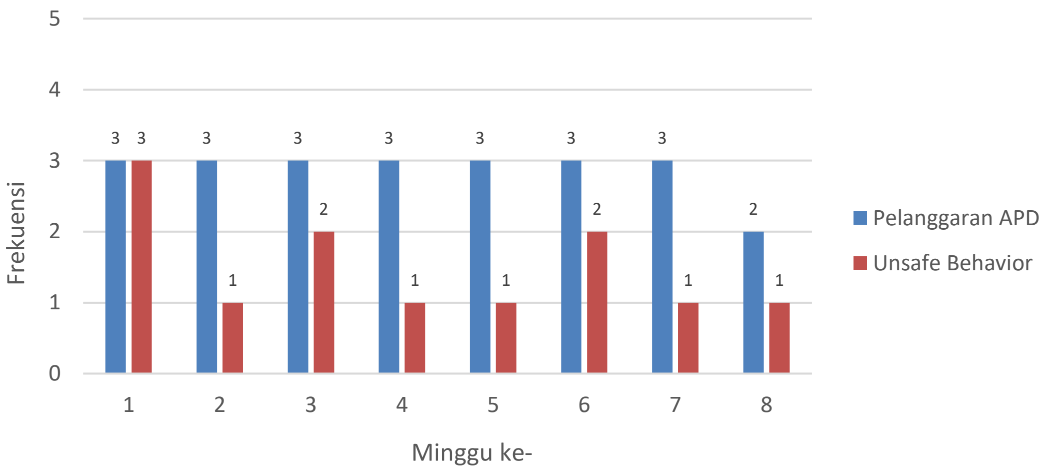


**Figure 1.** Weekly Distribution of Baseline Safety Findings During January-February 2026

Following implementation of the drone-based monitoring system during March-April 2026, a substantial reduction in overall safety findings was observed. Only 15 safety findings were recorded throughout the post-intervention period compared with 35 findings during baseline monitoring. PPE violations decreased to 9 cases (60%), while unsafe behavior declined to 6 cases (40%). Although PPE violations remained the most frequently observed safety issue, their absolute frequency was considerably lower than before the intervention. Continuous aerial surveillance enabled safety inspectors to monitor multiple work locations simultaneously and provided visual documentation from viewpoints that were previously inaccessible through conventional supervision. Consequently, workers showed greater compliance with safety procedures because monitoring became more visible, continuous, and less predictable than routine manual inspections. These observations show that drone deployment improved both monitoring effectiveness and workers' adherence to established safety requirements.

**Table 7**
Post-Intervention Safety Monitoring (March-April 2026)

| Type of Finding | Frequency | Percentage |
|---|---|---|
| PPE Violations | 9 | 60% |
| Unsafe Behavior | 6 | 40% |
| Total | 15 | 100% |

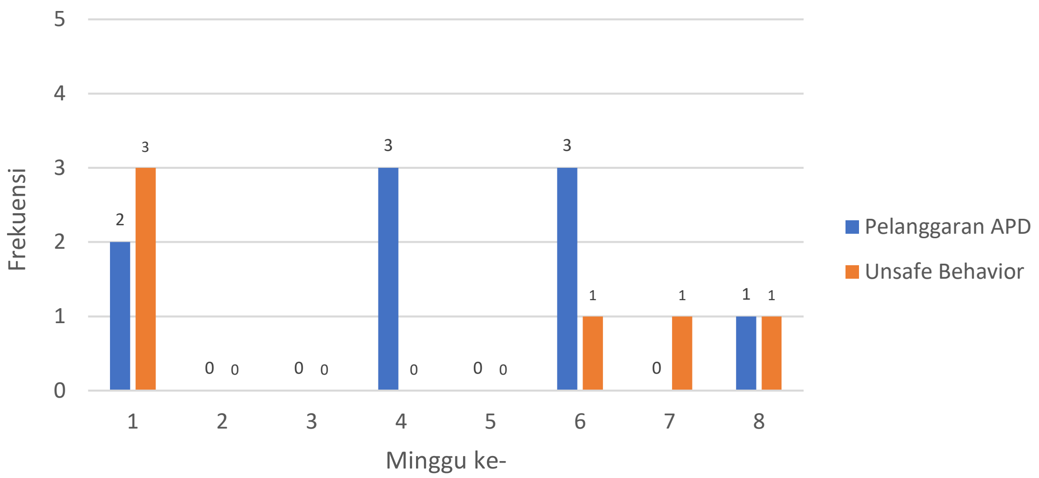


Figure 2. Weekly Distribution of Safety Findings Following Drone Implementation During March-April 2026

Comparison between baseline and post-intervention observations showed marked improvements in occupational safety performance after drone implementation. PPE violations decreased from 23 to 9 cases, corresponding to a reduction of 60.87%, Similarly, unsafe behavior decreased from 12 to 6 cases, showing a 50% reduction compared with baseline observations. These reductions show that the intervention successfully improved worker compliance with Full Body Harness requirements while simultaneously decreasing high-risk behaviors associated with fall-from-height incidents. The improvements were consistently observed across multiple monitoring periods rather than being restricted to isolated work shifts, suggesting that the intervention produced sustained behavioral changes throughout the observation period.

To determine whether the observed improvements were statistically significant, normality testing was first performed using the Shapiro-Wilk test. The analysis produced $W = 0.858$ ($p = 0.114$) for PPE compliance and $W = 0.827$ ($p = 0.056$) for unsafe behavior. Since both p-values exceeded the significance threshold of 0.05, the assumption of normality was satisfied, allowing the use of parametric statistical analysis. Consequently, differences between baseline and post-intervention observations were evaluated using the paired-sample t-test. Statistical testing showed significant differences between pre-and post-intervention measurements for both variables, indicating that drone implementation produced measurable improvements in occupational safety performance.

**Table 8**

Shapiro-Wilk Normality Test

| Variable | W | p-value |
|---|---|---|
| Pre_APD - Post_APD | 0.858 | 0.114 |
| Pre_Unsafe Behavior - Post_Unsafe Behavior | 0.827 | 0.056 |

The paired-sample t-test further confirmed the effectiveness of the intervention. PPE compliance showed $t = 4.25$ ($df = 7$, $p = 0.004$), whereas unsafe behavior yielded $t = 3.00$ ($df = 7$, $p = 0.020$). Because both p-values were below 0.05, statistically significant differences existed between baseline and post-intervention conditions. Moreover, the practical significance of the intervention was assessed using Cohen's d, which produced values of 1.50 for PPE compliance and 1.06 for unsafe behavior. According to Cohen's interpretation criteria, both values represent large effect sizes, indicating that drone-based monitoring generated not only statistically significant improvements but also substantial practical impacts on worker safety behavior. The larger effect size observed for PPE compliance suggests that workers responded particularly well to the increased visibility and consistency of drone-assisted supervision.

**Table 9**

Paired-Sample t-Test and Effect Size

| Variable | t | df | p-value | Effect Size (Cohen's d) |
|---|---|---|---|---|
| Pre_APD - Post_APD | 4.25 | 7 | 0.004 | 1.50 |
| Pre_Unsafe Behavior - Post_Unsafe Behavior | 3.00 | 7 | 0.020 | 1.06 |

In addition to behavioral improvements, implementation of drone monitoring substantially reduced occupational risks faced by safety inspectors responsible for supervising work-at-height activities. Fine-Kinney risk assessment conducted under conventional monitoring identified four principal hazards, including fall-from-height exposure, struck-by incidents during lifting operations, falling objects around scaffolding, and slip hazards on elevated access platforms. The highest risk score reached 900, classified as Very High Risk, while the remaining activities ranged from Substantial Risk to Very High Risk. These findings show that conventional supervision required inspectors to enter hazardous work areas, thereby exposing them to significant occupational risks. Consequently, improving monitoring methods was necessary not only to enhance worker compliance but also to protect safety personnel performing inspection activities.

**Table 10**

Fine-Kinney Risk Assessment Before Drone Implementation

| Activity | Risk Score | Risk Level |
|---|---|---|
| Observation at elevated structures | 900 | Very High Risk |
| Monitoring lifting operations | 540 | Very High Risk |
| Scaffolding observation | 252 | High Risk |
| Accessing stairs/platforms | 126 | Substantial Risk |

Following implementation of drone-assisted monitoring, the occupational risk profile changed substantially because safety inspectors no longer needed to routinely access elevated work areas. Instead, inspections were performed remotely from ground level using aerial visual monitoring, thereby minimizing direct exposure to hazardous environments. Risk scores declined dramatically, with elevated-area observation decreasing from 900 to 18, lifting-area supervision decreasing from 540 to 30, scaffolding observation decreasing from 252 to 14, and stair/platform access decreasing from 126 to 7. Most residual risks were classified as Acceptable Risk, while lifting-area monitoring remained within the Possible Risk category due to operational hazards associated with drone deployment. Importantly, the dominant risk shifted from human exposure risk toward equipment operational risk, such as temporary signal interruption or drone maneuverability issues, whose consequences were substantially less severe than conventional inspection hazards. These findings show that drone implementation not only improved workers' safety behavior but also fundamentally transformed occupational risk by replacing direct human exposure with safer remote observation methods.

**Table 11**
Fine-Kinney Risk Assessment After Drone Implementation

| Activity | Risk Score | Risk Level |
|---|---|---|
| Drone observation of elevated structures | 18 | Acceptable Risk |
| Drone monitoring of lifting operations | 30 | Possible Risk |
| Drone observation of scaffolding | 14 | Acceptable Risk |
| Ground-level monitoring without platform access | 7 | Acceptable Risk |

**Table 12**
Comparison of Occupational Risk Before and After Drone Implementation

| Activity | Risk Score (Before) | Risk Level (Before) | Risk Score (After) | Risk Level (After) |
|---|---|---|---|---|
| Observation of elevated structures | 900 | Very High Risk | 18 | Acceptable Risk |
| Monitoring lifting operations | 540 | Very High Risk | 30 | Possible Risk |
| Scaffolding observation | 252 | High Risk | 14 | Acceptable Risk |
| Access to stairs/platforms | 126 | Substantial Risk | 7 | Acceptable Risk |

## 2. Discussion

The findings show that drone-based safety monitoring significantly improved personal protective equipment (PPE) compliance during work at height in the petrochemical industry, with PPE violations decreasing from 23 to 9 cases (60.87%) and a statistically significant improvement confirmed by the paired sample t-test ($p = 0.004$; Cohen's $d = 1.50$). Compared with conventional supervision, drone deployment expanded monitoring coverage, improved visibility, and enabled continuous observation of elevated work areas, allowing unsafe practices to be detected more effectively. These findings are consistent with the Theory of Planned Behavior proposed by Ajzen in 1991, suggesting that continuous surveillance strengthens workers' perceived behavioral control and reinforces compliance with safety requirements (Nguyen & Le, 2026). The results also support the principles of Behavior Based Safety introduced by Geller in 2005, in which systematic observation and timely feedback encourage safer work practices (Geller, 2024). Similar conclusions were reported by Sasmitha *et al.* (2025), who identified effective supervision as a key determinant of PPE compliance. From the perspective of the Swiss Cheese Model (Reason, 2000), improved PPE compliance strengthens organizational safety barriers, although the remaining violations indicate that safety culture, worker competency, PPE comfort, and management commitment continue to influence compliance.

Drone implementation also significantly reduced unsafe behavior from 12 to 6 observed incidents (50%), with statistical analysis confirming a significant effect ($p = 0.020$; Cohen's $d = 1.06$). Unsafe behaviors, including improper working positions and deviations from established procedures, became less frequent following the intervention, showing that drone monitoring positively influenced workers' safety behavior. These findings support Heinrich's in 1931 by Human Factors Theory, which identifies unsafe acts as a primary contributor to workplace accidents (Stockel, 2023). Likewise, Hossain *et al.* (2025) emphasized that unsafe behavior remains one of the dominant causes of work-at-height accidents, showing the importance of behavioral interventions. According to the Swiss Cheese Model (Reason, 2000), reducing unsafe behavior minimizes active failures that may trigger accidents when organizational defenses weaken. The findings further reinforce the Behavior Based Safety framework proposed by Geller in 2005, showing that continuous behavioral observation supported by drone technology contributes to sustainable improvements in workplace safety.

The combined reduction in PPE violations and unsafe behavior indicates that drone-assisted monitoring strengthens proactive occupational health and safety (OHS) performance rather than merely improving inspection efficiency. These behavioral improvements represent important leading indicators because they show enhanced preventive controls before accidents occur, consistent with the safety performance framework proposed by Hale and Hovden in 1998. The results also support the Human Technology Integration perspective, which emphasizes that appropriately designed technologies enhance human capability in operational decision-making and risk control. Khurram *et al*. (2025) similarly argued that safety technologies should compensate for human observational limitations to improve organizational resilience during hazardous operations. The findings are consistent with the socio-technical systems perspective, which considers workplace safety as the result of interactions among human behavior, technology, organizational processes, and environmental conditions. Collectively, these findings indicate that drone technology functions as an effective complement to conventional supervision within integrated OHS management systems.

Risk assessment using the Fine-Kinney method further showd that drone implementation substantially reduced occupational risks faced by OHS personnel during work-at-height supervision. Under conventional monitoring, inspectors were exposed to Very High, High, and Substantial Risk conditions while observing elevated work areas, lifting operations, scaffolding, and access routes, reflecting the inherent hazards described in the Indonesian Minister of Manpower Regulation (Permenaker) No. 9 of 2016. These findings are consistent with the risk theory proposed by Kaplan and Garrick in 1981, which explains risk as the interaction of probability, exposure, and consequence (Zuzak *et al*., 2022). By transferring monitoring activities from elevated locations to ground-level remote observation, drone implementation reduced most activities to Acceptable Risk, while supervision near lifting operations decreased to Possible Risk. This shift substantially reduced direct human exposure while maintaining effective safety oversight, demonstrating that drone technology can improve both operational safety and supervisory effectiveness. Although residual risks related to drone operation remain, they are generally associated with equipment performance and operational handling rather than direct exposure to life-threatening work-at-height hazards.

## Conclusion

The implementation of a drone-based occupational safety monitoring system significantly improves safety performance during work at height in the petrochemical industry. Drone-assisted monitoring increased compliance with Full Body Harness use by reducing PPE violations from 23 to 9 cases (60.87% reduction), with statistical analysis confirming a significant improvement ($p = 0.004$) and a large practical effect (Cohen's $d = 1.50$). The system also significantly reduced unsafe behavior from 12 to 6 cases (50% reduction), supported by a significant paired sample t-test result ($p = 0.020$) and a large effect size (Cohen's $d = 1.06$), showing that drone monitoring effectively promotes safer worker behavior compared with conventional supervision. The Fine-Kinney risk assessment showed substantial reductions in the occupational risks associated with safety monitoring activities, with observation at elevated areas decreasing from a risk score of 900 (Very High Risk) to 18 (Acceptable Risk), lifting area supervision from 540 to 30 (Possible Risk), scaffolding observation from 252 to 14 (Acceptable Risk), and access to stairs and work platforms from 126 to 7 (Acceptable Risk). Drone implementation not only reduced direct exposure of occupational safety personnel to high-risk environments but also transformed the monitoring risk profile from human exposure risk to lower-consequence equipment operational risk.

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