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# PPE non-compliance among construction workers: An assessment of contributing factors utilizing fuzzy theory

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ABSTRACT

*Introduction*: Construction practitioners are at a disproportionately higher risk of fatal and nonfatal injuries compared to practitioners from other industries. The absence of and inappropriate use of personal protective equipment (PPE), hereinafter referred to as PPE non-compliance, are major causes of fatal and nonfatal injuries at construction workplaces. *Method:* Accordingly, a robust 4-step research methodology was employed to investigate and assess factors that contribute to PPE non-compliance. As a result, 16 factors were identified utilizing literature review and ranked utilizing fuzzy set theory and K-means clustering. Top among them: inadequate safety supervision, poor risk perception, lack of climate adaptation, lack of safety training, and lack of management support. *Results:* Managing construction safety in a proactive manner is vital to eliminate or minimize construction hazards and improve overall site safety. Thus, proactive measures to address these 16 factors were identified utilizing a focus group methodology. The validation of the statistical findings with that of the focus groups of industry professionals provides validation of the findings as both practical and actionable. *Practical Applications:* This study significantly contributes to construction safety knowledge and practice which, in turn, aids academic researchers and construction practitioners in their continuous efforts to reduce fatal and nonfatal injuries among construction workers.

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## 1. Introduction

The U.S. construction industry has maintained an average share of fatalities (~20%) that is greater than its average representation within the overall workforce (~4.3%) for the last 10 years. In 2020, the construction industry's share of fatalities was 21.2% (i.e., 1,008 fatalities), whereas its representation within the overall workforce was 4.1%. Fig. 1 shows the fatal injury data by industry and the construction occupation employment estimates from the U.S. Bureau of Labor Statistics (BLS, 2021).

To better understand the numbers presented in Fig. 1 and the disparity in fatalities between construction workers and non-construction workers, an odds ratio was calculated utilizing the numbers of fatalities among construction workers and non-construction workers, along with their representation in the U.S. workforce. Equation (1) was used to calculate the odds ratio by the research team for the years between 2010 and 2020.

$$\textit{Odds Ratio} = \frac{p/(1-p)}{q/(1-q)} \tag{1}$$

Where:

p: Percentage of fatalities among construction workers in a specific year (fatality cases/construction population).
q: Percentage of fatalities among all workers, not including construction workers in a particular year (fatality cases/all workforces not including construction).

The overall resulting odds ratio for the 2010 to 2020 period was 5.57 (95%; confidence interval (CI): 5.45–5.65). This result indicates that construction workers, on average, are 5.57 times more likely to be killed than non-construction workers in U.S. workplaces. The 95% CI of 5.45 to 5.65 means that one can be 95% confident that the true odds ratio lies somewhere between 5.45 and

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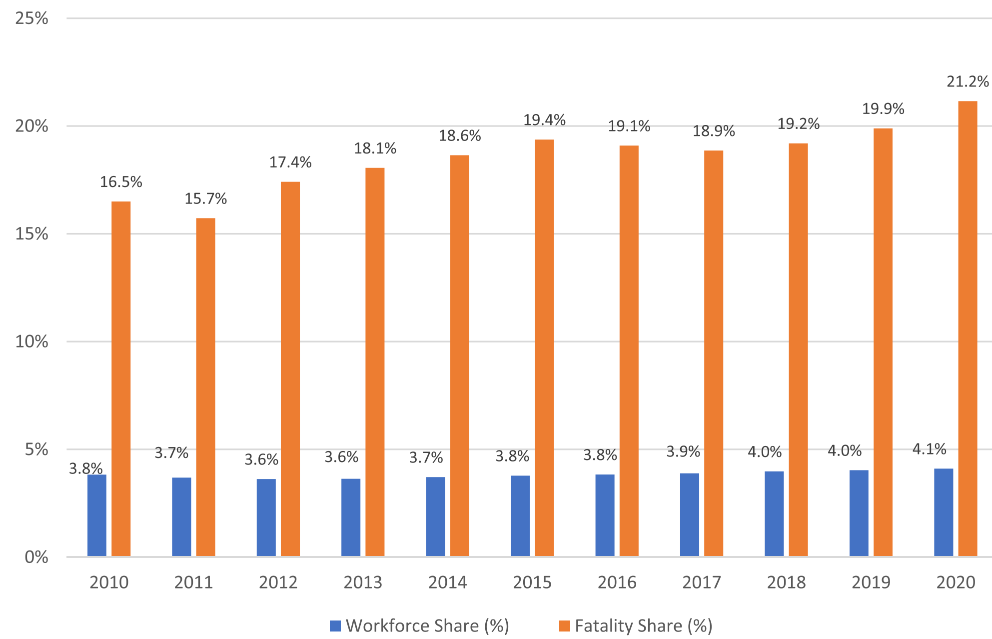


**Fig. 1.** Construction Workforce and Fatality Shares.

5.65. A 95% confidence interval that does not eclipse 1.00 would commonly be interpreted as a statistically significant odds ratio. The odds ratio was 6.26 in 2020, which is the highest since 2010. These alarming odds ratios highlight the importance of further interventions to improve the overall safety performance of construction workers.

According to Fang and Zhang (2012), detecting hazards is the first step in controlling them. Control responses to a recognized hazard include elimination, engineering, administration, and personal protective equipment (PPE). Clearly, PPE is the last resort in the hierarchy of control because the appropriate use of PPE depends on many factors, including worker attitude and overall safety culture and climate. Fatal and nonfatal injuries are a consistent challenge associated with inappropriate utilization of PPE (Hamid et al. 2008; Lette et al. 2018; Lestari et al. 2019). Several studies have reported that lack of PPE is the main cause of fall incidents (Chi et al. 2009; Lestari et al. 2019; Wong et al. 2021). According to Al-Bayati and York (2018), 85% of examined fatal fall incidents among Hispanic workers in the United States were associated with not using the required PPE. Similarly, Kang et al. (2017) found that 70% of all fall incidents involved a lack of PPE. Construction workers who do not use PPE are three times more likely to be injured than those who do (Lette et al., 2018). Melzner et al. (2013) suggest that wearing PPE contributes to a roughly 30% reduction in fall accidents. Thus, addressing the causes of inappropriate utilization of PPE should improve safety outcomes in construction workplaces (Martin et al., 2021). Safety management practices (e.g., disciplinary action, safety training, and effective safety communication) are critical contributors to the appropriate utilization of PPE among construction workers (Tam & Fung, 2012; Wong et al., 2020). The appropriate use of PPE is one of the most important safety factors in avoiding physical injuries (Ismail et al., 2012; Gunduz & Ahsan, 2018).

Safety supervision, in terms of resolving safety issues promptly and welcoming reports of safety issues, seems to be ineffective in increasing construction workers' use of PPE (Wong et al., 2020; Al-Bayati et al., 2019). Clearly, the role of safety culture (e.g., the actions of upper management and safety personnel) has a significant influence on worker behavior (Al-Bayati et al., 2019). For example, Mohajeri et al. (2021) reported that construction workers may rarely use PPE provided to them by contractors. Therefore, safety management practices that lead to strict safety policies are highly recommended and even welcomed by workers who prefer consistent enforcement of PPE use (Chen & Jin, 2015). On the other hand, safety management should also provide incentives to workers to encourage them to follow safety policies and address the physical discomfort that PPE may cause during various weather conditions, such as heat and high humidity (Man et al., 2021).

## 2. Research objectives and methodology

This study aims to reduce fatal and nonfatal injuries among construction workers. Accordingly, the objective of this study is to improve the industry's understanding of the factors that contribute to PPE non-compliance and improve the understanding of how to engineer and manage them. This objective will be met by answering the following research questions:

1. What are the factors that contribute to PPE non-compliance in construction workplaces?
2. What are the factors with predominant impact, and how can these factors be grouped based on similarity and prioritized based on importance to help decision makers use a separate strategy for each group?
3. What are the recommended proactive measures to engineer and manage the contributing factors to PPE non-compliance?

A 4-step research methodology was designed to answer the research questions: (1) a systematic literature review to identify factors that contribute to PPE non-compliance; (2) a questionnaire-based survey of subject-matter experts (SMEs) to rank the identified factors (i.e., a criticality assessment); (3) clustering factors into groups based on their rankings utilizing a K-means algorithm; and (4) a focus group study to validate the findings and develop a set of recommendations to engineer and manage the undesirable influence of identified factors. The following subsections discuss each step of the research methodology and its findings.

### 2.1. Literature review

A literature review is an effective method of gaining insight into a particular topic and evaluating what is currently known about the subject (Jesson et al., 2011; Fink, 2019). The authors employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method to carry out the literature review. PRISMA is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. The methodology of the research includes four major phases: identification, screening, eligibility, and inclusion, see Fig. 2.

The American Society of Civil Engineers (ASCE) online library and Science Direct databases were searched to identify relevant literature. The search was conducted with related keywords (e.g., personal protective equipment [PPE], construction accidents, non-use of PPE), focusing on published literature between 2002 and 2020. The first phase of the literature review resulted in 622 journal papers and conference proceedings. Accordingly, a literature screening was performed by skimming the articles' titles and abstracts, which resulted in 73 papers related to the research question. Accordingly, an eligibility evaluation was conducted using the 73 papers. Two members of the research team conducted the eligibility evaluation separately to avoid any potential errors. As a result, 19 related papers were included in the full literature review to identify the factors that contribute to PPE non-compliance among construction workers. Table 1 shows the 19 articles that have been included in the full literature review.

The literature review suggests that there are 16 factors that contribute to PPE non-compliance. Furthermore, a careful examination of the identified factors suggests that they can be categorized into the following four categories: PPE design factors, construction safety climate factors, construction safety culture factors, and other factors. Table 2 provides an example of each factor based on the reviewed literature. An explanation of the factor categorization follows:

- PPE design factors: Two factors are related to design shortcomings:

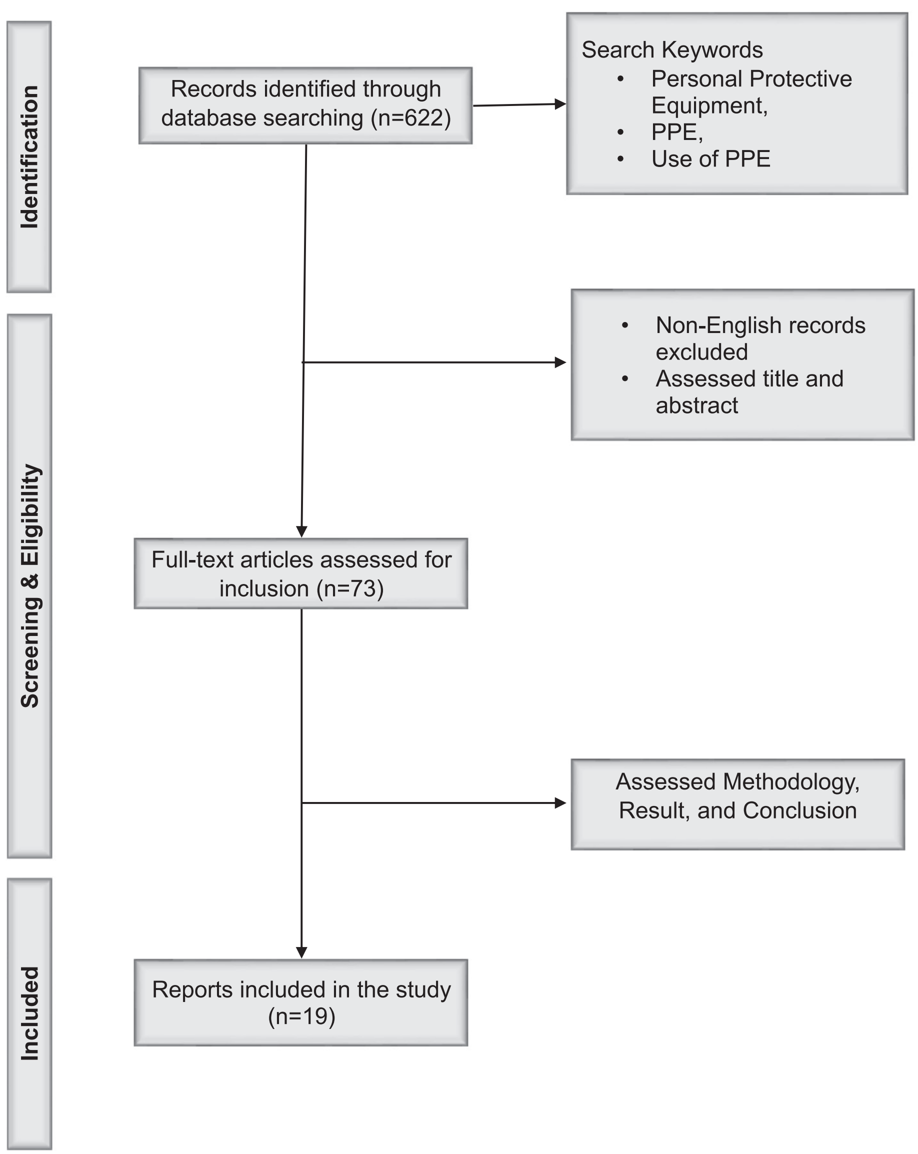


**Fig. 2.** The Literature Review Methodology.

**Table 1**
Articles Included in the Full Review.

| Author(s) – Country | Article Title | Research Methods (Sample Size) |
|---|---|---|
| Wagner et al. (2013) – United States | Relationship between personal protective equipment, self-efficacy, and job satisfaction of women in the building trades | Survey (75) |
| Lombardi et al. (2009) – United States | Factors influencing worker use of personal protective eyewear | Focus group (51) |
| Man et al. (2017) – Hong Kong | Risk-taking behaviors of Hong Kong construction workers–A thematic study | Interview (40) |
| Dasandara and Dissanayake (2021) – Sri Lanka | Limiting reasons for the use of personal protective equipment among construction workers: Case studies in Sri Lanka | Interview (14) |
| Shokouhi et al. (2021) – Iran | Predicting the probability of occupational fall incidents: A Bayesian network model for the oil industry | Survey (1,000) |
| Menzel and Gutierrez (2010) – United States | Latino worker perceptions of construction risks | Focus group (30) |
| Arcury et al. (2014) – United States | Occupational safety beliefs among Latino residential roofing workers | Interviews (10) |
| Teran et al. (2015) – United States | Promoting adoption of fall prevention measures among Latino workers and residential contractors: Formative research findings | Survey (31) |
| Ulang et al. (2014) – Malaysia | Construction site workers' awareness on using safety equipment: Case study | Survey (60) |
| Wong et al. (2020) – Hong Kong | Critical factors for the use or non-use of personal protective equipment amongst construction workers | Interview (60) |
| Choudhry and Fang (2008) – Hong Kong | Why operatives engage in unsafe work behavior: Investigating factors on construction sites | Interviews (12) |
| Sehsah et al. (2020) – Egypt | Personal protective equipment (PPE) use and its relation to accidents among construction workers | Survey (382) |
| Izudi et al. (2017) – Uganda | Use of personal protective equipment among building construction workers in Kampala, Uganda | Survey (385) |
| Rafindadi et al. (2021) – Malaysia | Significant factors that influence the use and non-use of personal protective equipment (PPE) on construction sites—Supervisors' perspective | Survey (96) |
| Chi et al. (2005) – Taiwan | Accident patterns and prevention measures for fatal occupational falls in the construction industry | Case analysis (621) |
| Li et al. (2017) – Hong Kong | Investigation of the causality patterns of non-helmet use behavior of construction workers | Data analysis (43) |
| Martin et al. (2021) – United States | Exploring the role of PPE knowledge, attitude, and correct practices in safety outcomes on construction sites | Survey/interview (100) |
| Dale et al. (2021) – United States | Flow-down of safety from general contractors to subcontractors working on commercial construction projects | Survey (1,279) |
| Tam et al. (2004) – China | Identifying elements of poor construction safety management in China | Survey (60) |

1) Poor quality, fit, and comfort
2) Lack of climate adaptation (e.g., workers do not want to wear poorly adapted PPE such as helmets or gloves in hot/cold climates)

- Construction safety climate factors: The construction safety climate category includes factors related to the actions of workers and frontline supervisors (Al-Bayati et al., 2019). For example, the perception that PPE use increases work effort and time requirements and inadequate safety supervision are related to field workers and frontline supervisors. Factors within this category not only impact the individuals who conduct unsafe actions but also discourage other workers from using safety equipment, which compromises overall safety performance. Similarly, frontline supervisors who fail to emphasize and enforce the use of safety equipment also contribute to PPE non-compliance. There are seven factors within this category:
  1) Workers believe that PPE increases work time
  2) Workers believe that PPE increases work effort
  3) Workers believe that PPE increases restrictions
  4) Inadequate safety supervision: Safety supervision is necessary to enforce compliance with safe work practices. Otherwise, workers may display a negligent attitude and disregard safety rules (Martin et al., 2021)
  5) Peer pressure
  6) Poor worker risk perception [i.e., poor worker assessments of the risks they are exposed to (Wong et al., 2020)]
  7) Performance pressure
- Construction safety culture factors: The corporate construction safety culture category includes factors that are related to the actions of upper management and safety personnel, such as lack of safety training and upper management support (Al-Bayati et al., 2019). It is worth noting that there are three dimensions of safety culture: corporate, psychological, and behavioral (Zou & Sunindijo, 2015). An explanation of these dimensions is beyond the scope of this paper. However, interested readers may refer to Al-Bayati et al. (2019) and Zou and Sunindijo (2015), where this topic is discussed in more detail. Clearly, firm size contributes to a lack of safety rules and policies as well as a lack of PPE availability and accessibility. Al-Bayati (2021a) suggested that there is a statistically significant positive correlation between firm size and construction safety culture because smaller construction firms have limited resources to create and maintain adequate safety and health policies. There are four factors within this category:
  1) Lack of safety training
  2) Lack of management support
  3) Lack of safety rules and regulations
  4) Lack of PPE availability and accessibility
- Other factors: There are three factors within this category: (1) unstable employment status (temporary and seasonal employment), (2) somatic health effects, and (3) cultural and language barriers. Temporary workers who are hired and paid by a staffing agency are at increased risk of work-related injury and illness (Occupational Safety and Health Administration (OSHA, 2014). Some workers cannot wear PPE due to physical and mental stress, especially in confined or poorly ventilated areas. On the other hand, it has been suggested that cultural and language barriers contribute to higher fatality rates among ethnic minority construction workers (e.g., the Hispanic workforce in the United States; (Thompson & Siddiqi, 2007; McGlothlin et al., 2009; Al-Bayati et al., 2017). Therefore, training modules designed to overcome cultural and language barriers should be employed (Al-Bayati, 2019). Hispanic workers do not always receive the necessary PPE due to their employment status,

**Table 2**
Causes of personal protective equipment (PPE) non-compliance.

| | Factors | Factor Explanation Based on the Reviewed Articles | References |
|---|---|---|---|
| PPE Design Factors | F01. Poor quality, fit, and comfort | • Gender-specific or smaller/larger sized PPE (e.g., gloves) is not available.<br>• Lack of comfort/fit and fogging and scratching of eyewear may inhibit their usage.<br>• Distortion and clarity problems associated with eyewear may result in somatic effects, such as headaches, dizziness, or nausea.<br>• PPE is uncomfortable or ill-fitting when worn during all necessary working hours.<br>• PPE is not stylish. | Lombardi et al. (2009); Wagner et al. (2013); Man et al. (2017); Wong et al. (2020); Arcury et al. (2014); Wong et al. (2020); Sehsah et al. (2020); Rafindadi et al. (2021); Shokouhi et al. (2021) |
| | F02. Lack of climate adaptation | • Workers reported discomfort wearing poorly adapted PPE in hot/cold climates. | Dasandara and Dissanayake (2021) |
| Safety Climate Factors | F03. Workers believe that PPE increases work time | • Workers think PPE delays their work because the use of some PPE items (such as harnesses) reduces mobility (i.e., perceived as an impediment to productivity)<br>• Workers want to complete tasks in the shortest time possible; thus, they often fail to take safety measures that require considerable time.<br>• Workers believe that contractors do not want them to use PPE because the PPE prevents them from working faster.<br>• Interviewees (roofers) believe that they can work faster with no PPE. | Wong et al. (2020); Arcury et al. (2014); Man et al. (2017) |
| | F04. Workers believe that PPE increases work effort | • Workers believe that safety measures require significant effort. For example, some workers prefer to use ladders that do not match safety standards instead of establishing a working platform when working in high areas because they feel that establishing a platform requires too much effort. | Wong et al. (2020); Arcury et al. (2014); Man et al. (2017) |
| | F05. Workers believe that PPE increases restrictions | • Working in a limited space is inconvenient with the use of a safety helmet because head movement is restricted.<br>• Some workers think there is limited workspace for them to use PPE.<br>• Workers report that PPE restricts movement, becomes tangled, is heavy, and impedes communication. Workers feel that these restrictions in range of movement are hazards, and they report feeling less safe wearing PPE because it makes their movements awkward. | Wong et al. (2020); Sehsah et al. (2020); Rafindadi et al. (2021) |
| | F06. Inadequate safety supervision | • Supervisors try to maintain good relationships with workers to complete projects on time and as expected. Therefore, management purposely tolerates the situation without insisting on PPE use.<br>• Workers remove PPE when managers are not in sight. It is obvious in this context that workers are motivated to use PPE only through transactional leadership.<br>• There is a lack of involvement of external responsible parties in monitoring safety supervision at sites. | Dasandara and Dissanayake (2021); Ulang et al. (2014); Choudhry and Fang (2008); Rafindadi et al. (2021); Martin et al. (2021) |
| | F07. Peer pressure | • Some co-workers tease and make fun of those who choose to use PPE.<br>• Some workers want to prove they are "tough guys" and are not scared of getting hurt. | Choudhry and Fang (2008); Wong et al. (2020); Arcury et al. (2014); Menzel and Gutierrez (2010); Man et al. (2017); Lombardi et al. (2009) |
| | F08. Poor risk perception | • Some experienced workers rely on their experience, believing that they don't need PPE; some young workers often see work as an adventure and are overconfident.<br>• Some workers think the chance of accidents is small.<br>• Some workers do not accept the concept that they should be motivated to wear PPE for their own safety. They view PPE only as a job requirement.<br>• Workers state that their risk-taking behaviors, such as smoking at work and not using a safety harness, have become habits. Although the construction workers know that these behaviors are dangerous, they still perform such behaviors out of repetition and habit rather than conscious deliberation of costs and benefits. | Lombardi et al. (2009); Man et al. (2017); Dasandara and Dissanayake (2021); Teran et al. (2015); Rafindadi et al. (2021); Li et al. (2017) |
| | F09. Performance pressure | • Workers state that productivity bonuses have led them to achieve higher production at the expense of safety.<br>• Workers report experiencing performance pressure from their supervisors. | Rafindadi et al. (2021); Choudhry and Fang (2008); Arcury et al. (2014) |
| Safety Culture Factors | F10. Lack of | | Lombardi et al. (2009); Dasandara and Dissanayake |

**Table 2** (*continued*)

| | Factors | Factor Explanation Based on the Reviewed Articles | References |
|---|---|---|---|
| | safety training | • Most workers without safety training report working either for themselves or for small companies with no formal safety training program. Reported use of PPE is lowest among these workers.<br>• There is a lack of safety education and training on the appropriate use of PPE.<br>• There is a lack of worker knowledge of all applicable safety laws at construction sites.<br>• Workers do not know how to use PPE.<br>• Some workers are uneducated. They cannot read and understand safety material (illiteracy). | (2021); Teran et al. (2015); Ulang et al. (2014); Choudhry and Fang (2008); Sehsah et al. (2020); Izudi et al. (2017); Rafindadi et al. (2021); Chi et al. (2005); Li et al. (2017); Martin et al. (2021) |
| | F11. Lack of management support | • Management commitment to safety for better safety policies and procedures and effective safety training is lacking.<br>• No one is enforcing labor laws or ensuring contractors follow regulations. This lack of enforcement allows contractors to operate with an emphasis solely on production, without feeling any pressure to follow safety guidelines or labor laws in general.<br>• Good practices, such as the use of PPE while working, are not rewarded or appreciated by management.<br>• Management makes inadequate efforts to provide adequate PPE. | Tam et al. (2004); Dale et al. (2021); Rafindadi et al. (2021); Choudhry and Fang (2008); Ulang et al. (2014); Teran et al. (2015); Arcury et al. (2014); Lombardi et al. (2009) |
| | F12. Lack of safety rules and policies | • There are no specific rules and regulations in place with regard to the use of PPE, especially for small and medium-sized enterprises (SMEs). They are in a flexible mode in terms of following rules and regulations when compared to large-scale construction organizations.<br>• Pre-task evaluations are not always performed. As a result, there is a severe lack of effective enforcement, including safety inspections, risk assessments, and accident reporting. | Teran et al. (2015); Rafindadi et al. (2021); Martin et al. (2021); Dale et al. (2021) |
| | F13. Lack of PPE availability and accessibility | • Small contractors are often not equipped to work on hazardous sites because they lack proper PPE, yet they engage in projects that require such equipment.<br>• Some workers cannot always get PPE when they need it.<br>• Even though it is a violation of Occupational Safety and Health Administration PPE standards, some workers report being required to purchase their own PPE.<br>• Some workers perceive that their boss (supervisor) does not have the money to buy PPE for workers, so they fail to use PPE. | Tam et al. (2004); Rafindadi et al. (2021); Sehsah et al. (2020); Wong et al. (2020); Teran et al. (2015); Shokouhi et al. (2021); Dasandara and Dissanayake (2021); Man et al. (2017); Lombardi et al. (2009) |
| Other Factors | F 14. Unstable employment status | • Temporary and casual workers are less likely to use PPE than permanently employed workers.<br>• Undocumented workers cannot ask their employers for PPE because they are afraid of reprisal from employers if any safety concessions are requested, and they do not complain even when injuries occur because they need consistent work to support their families. | Dasandara and Dissanayake (2021); Arcury et al. (2014); Teran et al. (2015); Ulang et al. (2014); Izudi et al. (2017) |
| | F15. Somatic health effects | • Wearing PPE causes stress in hot, sunny, confined, and/or poorly ventilated areas.<br>• Poor health conditions lead some workers to abandon the use of PPE. | Lombardi et al. (2009); Dasandara and Dissanayake (2021); Sehsah et al. (2020) |
| | F16. Cultural and language barriers | • The participants (e.g., Latino workers) did not insist that supervisors provide safety gear because they felt intimidated by communicating with a person in authority (a traditional Latino value).<br>• Different lifestyles from different cultures have discouraged the use of PPE. | Menzel and Gutierrez (2010); Dasandara and Dissanayake (2021) |

which forces them to value job security over speaking up about safety issues (Grzywacz et al., 2012; Shrestha & Menzel, 2014; Al-Bayati et al., 2017).

### 2.2. Subject-matter experts (SMEs) – criticality assessment

This step aims to perform a criticality assessment (i.e., factor ranking) of the 16 factors identified in the literature review. Within this study context, the SMEs are construction practitioners with at least one year of experience. To improve the accuracy of the criticality assessment, fuzzy set theory (FS) was applied. FS is a robust system where no precise inputs are required since it can deal with subjective and imprecise judgments. FS was used in this study to quantify the verbal opinions and subjective judgments of the SMEs who participated in the study. A fuzzy number $P(\Theta)$ refers to a continuous set of possible values, where each value has a membership function that varies between 0 and 1. Typically, $P(\Theta)$ is represented as triangular, Gaussian, or trapezoidal fuzzy numbers to convert verbal/linguistic expressions by experts into fuzzy numbers. According to Li et al. (2012), triangular fuzzy numbers provide more precise descriptions and accurate results than the other representations. A triangular $P(\Theta)$ includes three values, where $P$

$(\Theta) \cong (\theta_1, \theta_2, \theta_3)$, where $\theta_2$ has the membership function of 1, and the values between $\theta_2$ and $\theta_1$ or $\theta_3$ have membership functions between 1 and 0. Values less than $\theta_1$ or greater than $\theta_3$ have a membership function of zero (Emrouznejad & Ho, 2017).

The triangular fuzzy numbers were selected by including three components for each linguistic term (i.e., fuzzification). Fig. 3 shows a graphical representation of the scaled triangles representing the linguistic terms to be assigned by each expert. The experts were asked to select the contribution level of each factor affecting PPE non-compliance in construction workplaces using linguistic terms (i.e., none, low, moderate, high, absolute).

The assessments of experts were combined using the linear opinion pool (LOP), where $P_i(\theta)$ is a fuzzy triangular number [denoted by $P(\theta) = (a, b, c)$] assigned by the experts, and $w_i$ is the percentage of experts who assigned $P_i(\theta)$.

$$P(\theta) \cong \sum_{i=0}^{n} [w_i \otimes P_i(\theta)] \tag{2}$$

The fuzzy triangular number $P(\theta)$ resulting from Equation (2) can be represented by a crisp number *Val (θ)* using Equations (3) and (4) as follows:

$$Val(\theta) = \int_0^1 Average(\theta_\alpha).d\alpha \tag{3}$$

Where $\theta_\alpha = \{x|F(x) \geq \alpha\}$ is the α-level of θ. The generalized formulation of a crisp number (i.e., defuzzification) *Val (θ)* can be achieved as shown in Equation (3) below:

$$Val(\theta) = \frac{\frac{1}{2}\int_0^1 [(b-a) \times \alpha + a + c - (c-b) \times \alpha]}{\int_0^1 d\alpha} = \frac{a + 2b + c}{4} \tag{4}$$

Accordingly, a survey was designed and submitted to the Human Subject Institutional Review Board (HSIRB) at Lawrence Technological University for review and approval. The survey questions are included in Table S1 of the Supplemental Materials. After approval, the invitations to participate were sent utilizing a convenience sample, which is a widespread research methodology in construction research due to the infeasibility of other sampling plans, such as probability-based sampling. The survey was administered between February and April 2022, and 184 valid responses were collected. A response is considered valid when the respondent takes more than 13 minutes to complete their response and does not provide any gibberish answers to open-ended questions. Thirteen minutes is the median time needed to complete the first 50 valid responses. The authors chose the median time instead of the average time because it is not severely impacted by delayed responses. In addition, responses from participants with less than one year of experience were removed. The main goal of these filters is to objectively remove low quality responses. Participants were presented with the study description and consent form, which led to the questionnaire only after the respondent voluntarily agreed to participate.

The participants represent diverse backgrounds of education, work experience, and firm size. Most of the participants (62.5%) had more than 10 years of experience, followed by participants with 6–10 years of experience (23.4%) and 1–5 years of experience (14.1%). The job descriptions of the participants fall within the following categories: construction workers (28.3%), construction supervisors (25.8%), safety personnel (15.8%), upper management (31.5%), and other (8.7%). The educational degrees of the participants fall within the following categories: Department of Labor registered apprenticeship (6; 3.3%), high school diploma (46, 25%), community college (31, 16.8%), Bachelor of Science or equivalent (75, 40.8%), master's degree or higher (17, 9.2%), and others (9, 4.9%). The participants' firm sizes in terms of the number of employees fall within the following categories: less than 10 employees (26, 14.1%), 10–50 employees (49; 26.6%), 51–100 employees (31; 16.8%), 101–250 employees (39; 21.2%), and more than 250 employees (39; 21.2%).

The experts assessed PPE factors using verbal expressions. This assessment was then converted into fuzzy numbers using Fig. 3 to model the inherited uncertainty from subjective input, then aggregated using Equation (2). For instance, for factor F1 "Poor Quality, Fit, and Comfort," 14 experts of 184 (7.6%) selected "absolute" associated with the fuzzy number of (0.75,1.00,1.00), 40 experts (21.7%) selected "high" associated with the fuzzy number of (0.50,0.75,1.00), 90 experts (48.9%) selected "moderate" associated with the fuzzy number of (0.25,0.50,0.75), 34 experts (18.4%) selected "low" associated with the fuzzy number of ((0.00,0.25,0.50), and 6 experts (3.2%) selected "none" associated with the fuzzy number of (0.00,0.00,0.25). The aggregated fuzzy number $P(\theta)$ for F1 is calculated as (0.28,0.52,0.76) using Equation (2); where, 0.076 * 0.75 + 0.217 * 0.5 + 0.489*0.25 + 0.184*0.00 + 0.032*0.00 = 0.28; 0.076 * 1.0 + 0.217 * 0.75 + 0.489*0.50 + 0.184*0.25 + 0.032*0.00 = 0.52; and 0.076 * 1.0 + 0.217 * 1.0 + 0.489*0.75 + 0.184*0.50 + 0.032*0.25 = 0.76. This result of the factor F1 indicates that, on the fuzzy scale shown in Fig. 3, the most likely value of P(θ) is 0.52, the upper likely value of P(θ) is 0.76, and the lower likely value of P(θ) is 0.28. The resulting values for F1 are

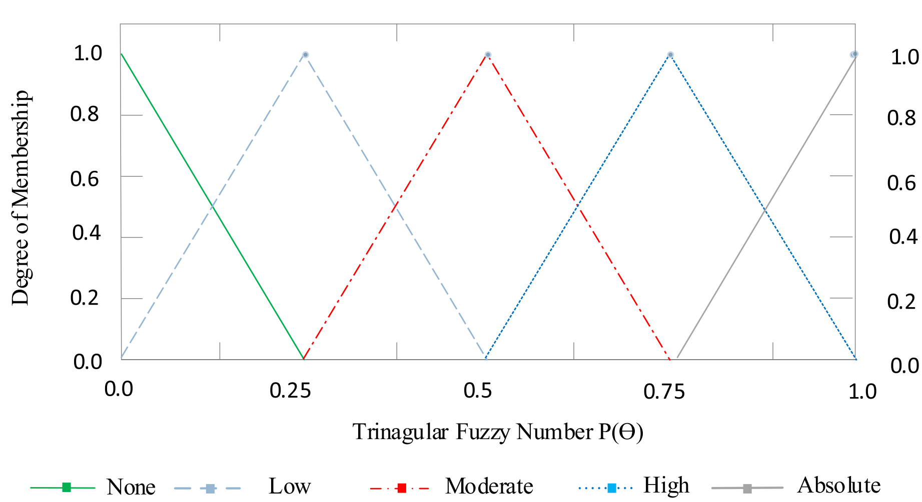


**Fig. 3.** Fuzzy Numbers Corresponding to Linguistic Terms.

**Table 3**
The Average Fuzzy Scores of the Study Factors.

| Factor | Average Score | Standard Deviation |
|---|---|---|
| F06. Inadequate Safety Supervision | 0.5625 | 0.2381 |
| F08. Poor Risk Perception | 0.5554 | 0.2325 |
| F02. Lack of Climate Adaptation | 0.5428 | 0.2037 |
| F01. Poor Quality, Fit, and Comfort | 0.5272 | 0.2131 |
| F05. PPE Increases Restrictions | 0.5187 | 0.2161 |
| F15. Somatic Health Effects | 0.5119 | 0.2402 |
| F04. PPE Increases Work Effort | 0.5014 | 0.2208 |
| F10. Lack of Safety Training | 0.4776 | 0.2513 |
| F03. PPE Increases Work Time | 0.4721 | 0.2323 |
| F09. Performance Pressure | 0.4575 | 0.2510 |
| F14. Unstable Employment Status | 0.4433 | 0.2474 |
| F11. Lack of Management Support | 0.4416 | 0.2547 |
| F13. Lack of PPE Availability and Accessibility | 0.4327 | 0.2504 |
| F12. Lack of Safety Rules and Regulations | 0.4263 | 0.2533 |
| F16. Cultural and Language Barriers | 0.3933 | 0.2442 |
| F07. Peer Pressure | 0.3923 | 0.2494 |

fuzzy triangular numbers, represented by $P(\theta) \cong (a, \mathrm{b}, \mathrm{c})$. However, it is necessary to transform fuzzy numbers into crisp values for the purpose of factor evaluation. To achieve this goal, the defuzzification process was applied. The fuzzy triangular numbers $P(\theta)$ have been represented by crisp numbers Val ($\theta$) using Equation (4). For example, for calculating the crisp number Val (Θ) for the factor F1"Poor Quality, Fit, and Comfort" with the value of a = 0.28, b = 0.52, and c = 0.76, the resulting crisp Val (Θ) is 0.527. Table 3 shows the criticality levels of the 16 factors. Table 3 shows the average crisp number of each factor. The factors are sorted from the highest crisp score to the lowest. Table 4 shows a sample of the defuzzification of 10 variable expressions that survey participants provided for factor 1.

### 2.3. K-means Clustering – Prioritizing Groups

Clustering is a method of identifying similar groups based on similarities in attributes, features, and other characteristics. Within this study context, clustering aims to arrange similar factors in terms of score values (i.e., defuzzification crisp numbers) into groups. This method helps decision makers better manage critical factors by prioritizing the allocation of any available mitigation resources (e.g., funding and safety personnel). Factor clustering enables decision makers to consider factors with predominant impact. Allocating factors into clusters also helps decision makers use a separate strategy for each group of factors based on the importance of those factors.

Several algorithms could be used for clustering. The most well-known algorithm types are connectivity, distribution, and centroid model (i.e., K-means algorithm). The K-means algorithm is used in this study because the assessed factors do not follow a specific distribution that can be used for clustering (Oskouie et al., 2017). The K-means algorithm is operated based on the notion of similarity that is derived from the closeness of a data point to the centroid of the clusters. K-means is an iterative algorithm that identifies and classifies similar groups of factors based on criticality. It includes two steps to identify the number of clusters and the factors that should be included within each cluster. The optimal number of clusters (K) is determined in the first step. The second step is clustering iterations, where each factor is allocated to the best fit cluster.

Techniques such as the elbow method and silhouette are typically used to determine K. It is noted that compared to the elbow method, the silhouette score is less prone to error as it uses a similarity measure that is based on the distance of the data points from their own clusters and the comparative distance to other clusters. Additionally, the elbow method uses only the sum of squared errors as the comparison factor. Thus, the silhouette score method is used to determine the number of clusters. The 16 factors were grouped using iterative $k$ values ranging from 2 to 10 clusters. Equation (5) was used to calculate the silhouette method's similarity measure ($S$). The value of $S$ range from −1 to 1, where a value near 1 indicates a well-matched cluster. Accordingly, the $k$ value that produces the highest average silhouette score is the most optimal clustering number.

$$S = \frac{b - a}{\max(a, b)} \tag{5}$$

Where $a$ represents the mean intra-cluster distance, and b represents the distance between a factor and the nearest cluster to which the factor does not belong.

The second step is clustering iterations. This step includes randomly assigning each factor to a cluster, computing cluster centroids, assigning the factor to the closest cluster centroid, and recomputing cluster centroids. It is worth mentioning that the computations and processing of these two steps are performed automatically by encoding the K-means algorithm into the R software. The optimal number of clusters must correspond to the maximum silhouette score (Yuan & Yang, 2019). Fig. 4 shows that the silhouette scores are close to each other between 2 and 6 clusters but are not identical. The maximum silhouette score is 0.62, which corresponds to five clusters. Accordingly, the 16 factors were assigned to 5 clusters, see Table 5.

### 2.4. Focus group study

Focus group meetings should be used to further understand and validate survey findings when using a non-probability survey sample. It is crucial to gather data utilizing a mixed methods methodology (e.g., a survey and focus group study) to gain confidence in the findings (Abowitz & Toole, 2010; Al-Bayati et al., 2017). According to Liamputtong (2011), focus group interviews gather a group of people to discuss a particular subject. Focus group inter-

**Table 4**
Example of Defuzzification Process.

| Experts | Verbal Expression | Fuzzy number | Min | Mean | Max | Crisp Number |
|---|---|---|---|---|---|---|
| 1 | Moderate | (0.25,0.50,0.75) | 0.25 | 0.5 | 0.75 | 0.5 |
| 2 | Moderate | (0.25,0.50,0.75) | 0.25 | 0.5 | 0.75 | 0.5 |
| 3 | High | (0.50,0.75,1.00) | 0.5 | 0.75 | 1 | 0.75 |
| 4 | Moderate | (0.25,0.50,0.75) | 0.25 | 0.5 | 0.75 | 0.5 |
| 5 | Moderate | (0.25,0.50,0.75) | 0.25 | 0.5 | 0.75 | 0.5 |
| 6 | High | (0.50,0.75,1.00) | 0.5 | 0.75 | 1 | 0.75 |
| 7 | None | (0.00,0.00,0.25) | 0 | 0 | 0.25 | 0.0625 |
| 8 | Moderate | (0.25,0.50,0.75) | 0.25 | 0.5 | 0.75 | 0.5 |
| 9 | High | (0.50,0.75,1.00) | 0.5 | 0.75 | 1 | 0.75 |
| 10 | Moderate | (0.25,0.50,0.75) | 0.25 | 0.5 | 0.75 | 0.5 |

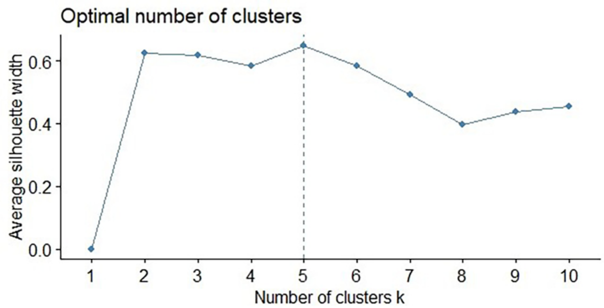


**Fig. 4.** The Optimal Number of Clusters.

views have unique features, such as enabling in-depth discussion and allowing interaction among participants. Methodologically, focus group studies engage the participants in a dynamic discussion for 1 to 2 hours to collect a range of participant opinions and reduce areas of misunderstanding.

Accordingly, focus groups were conducted by the research team to (1) validate the ranking of identified factors, (2) suggest proactive measures to effectively manage them, and (3) explore other potential contributing factors to PPE non-compliance. Two focus group meetings were conducted with four participants per session to enable in-depth discussion and allow interaction among participants. After the second session, the authors decided not to conduct additional focus group sessions due to the similarities between the results of previous sessions. The focus group study should come to an end when there is no new information collected; as a result, continuing interviews becomes pointless (Liamputtong, 2011). The two meetings took place in Southfield, MI, in May 2022.

Focus group sessions started with a presentation illustrating the following: construction workforce fatalities over a period of 10 years, the contribution of PPE non-compliance to these fatalities, and the survey findings. This presentation was designed to increase awareness among participants and to communicate the study objectives to motivate critical and in-depth discussion. During the discussion, the participants were also asked to complete a survey to record their agreement or disagreement with the survey findings and to suggest proactive measures to improve overall PPE compliance.

The average years of experience of participants within the construction industry was 15.6 years (SD = 13), and within the construction safety profession was 12 years (SD = 9). Based on a review of the criticality clusters, all participants suggested that the lack of safety training and lack of management support should be moved to the high criticality cluster. This suggestion is justifiable because actions of upper management and safety personnel significantly influence the behavior of field personnel, as suggested by Al-Bayati (2021b). Table 5 shows the clusters and their corresponding factors based on the survey findings as well as feedback and suggestions provided by focus group participants. Suggesting proactive measures is critical to eliminate or reduce the influence of the identified factors. Table 6 summarizes the proactive measures suggested by focus group participants.

Finally, the participants were asked to highlight other factors that may contribute to PPE non-compliance. Participants emphasized the contribution of financial constraints in terms of budget availability to purchase adequate PPE and hire the required number of qualified safety personnel. Participants also emphasized the difficulties of hiring and keeping enough safety personnel onsite to supervise and enforce PPE regulations due to financial constraints, especially among smaller construction firms. In addition, participants agreed that the client has an influence on overall safety performance. For example, one of the participants stated the following:

> "I used to work for a large concrete company, and one of my first jobs with them was on a nuclear facility. My first experience with this company, safety is very, very tight on a nuclear facility. However, the same company, same guys, literally, we all got shipped to a different site under a different client where the safety was not the focus; our safety program and performance completely changed."

**Table 5**
Criticality Assessment Clusters.

| Factor | K-cluster | Criticality Level |
|---|---|---|
| F06. Inadequate Safety Supervision | 1 | High |
| F08. Poor Risk Perception | | |
| F02. Lack of Climate Adaptation | | |
| F10. Lack of Safety Training* | | |
| F11. Lack of Management Support** | | |
| F01. Poor Quality, Fit, and Comfort | 2 | Moderate to High |
| F05. PPE Increases Restrictions | | |
| F15. Somatic Health Effects | | |
| F04. PPE Increases Work Effort | | |
| F03. PPE Increases Work Time | 3 | Moderate |
| F09. Performance Pressure | | |
| F14. Unstable Employment Status | 4 | Moderate to Low |
| F13. Lack of PPE Availability and Accessibility | | |
| F12. Lack of Safety Rules and Regulations | | |
| F16. Cultural and Language Barriers | 5 | Low |
| F07. Peer Pressure | | |

* F10 was moved to the high criticality level from the moderate criticality level based on focus group recommendations.
** F11 was moved to the high criticality level from the moderate to low criticality level based on focus group recommendations.

## 3. Theoretical and practical contributions

PPE non-compliance places construction workers who do not use PPE and their co-workers at risk; however, the blame for this action does not fall on workers' unsafe behavior alone. Unsafe behavior should be considered the direct cause of incidents and is a result of other factors such as lack of upper management support, safety personnel competence, and inadequate safety supervision (i.e., root causes). There are, in fact, many factors that contribute to this unsafe behavior of not using or inappropriately using PPE, as this study reveals. Identifying and prioritizing the contributing factors is vital to effectively engineer and manage construction safety and reduce fatal and nonfatal injuries.

On a theoretical level, this study will eventually contribute to human error theories and behavior models. Human error frameworks were originally developed and tested as a tool for investigating and analyzing the human causes (i.e., errors) of incidents (Garrett & Teizer, 2009). Human errors should be viewed as opportunities to investigate and identify the chain of events that led to the error. The accident-causing theory suggests that a series of coupled unsafe events leads to an incident (Liu, 2020). Thus, breaking the coupling relationship between unsafe events is crucial to prevent an incident. Human error theories should be embedded in behavior models that do not blame unsafe behavior alone, but workplace factors as well (Al-Bayati et al., 2021). In addition, human limitations should be considered. Upper management's commitment and safety personnel competency significantly contribute to field personnel's safety behavior (Al-Bayati et al., 2019). According to Choudhry and Fang (2008), human error and behavioral theories should stress the need for enhanced engineering and management techniques to deliver better-designed tasks and tools, while addressing human limitations (e.g., physical and psychological capabilities). Thus, the widely accepted suggestion

**Table 6**
Proactive Measures Suggested by Focus Group Participants.

| Cluster | ID | Proactive Measures |
|---|---|---|
| Cluster 1 (High Criticality) | F06 | • Encouraging, measuring, and monitoring frontline supervisor accountability<br>• Providing safety resources (e.g., designated site safety representatives) and fostering clear and professional communication between frontline supervisors and workers |
| | F08 | • Emphasizing the stakes involved in non-compliance with PPE<br>• Enhancing the critical thinking of workers through interactive risk perception training (dialoguing with workers about "what-if" and worst-case scenarios) |
| | F02 | • Improving PPE supply and providing specialized training and resources for wearing PPE in adverse weather conditions<br>• Providing cooling and heating stations for workers operating in intense weather conditions |
| | F10 | • Providing training at the same time that PPE is provided, to all new hires, and yearly refresher training<br>• Improving management support for educational and outreach programs |
| | F11 | • Emphasizing the reputational and financial costs of accidents due to PPE non-compliance<br>• Increasing leadership involvement, visibility (e.g., bringing management into the safety program to demonstrate PPE use), and accountability |
| Cluster 2 (Moderate to High Criticality) | F01 | • Improving the supply of PPE (different styles and sizes should be available)<br>• Improving PPE training and gaining worker input on PPE fit and comfort |
| | F05 | • Gaining worker input on potential restrictions and addressing them<br>• Conducting case-by-case evaluations to reach a resolution |
| | F15 | • Exploring PPE alternatives for individuals with health problems and employing case-by-case decision-making<br>• Raising worker awareness of the possible relationships between PPE use and certain health conditions |
| | F04 | • Getting employee feedback on PPE options that will not adversely affect effort and encouraging workers to suggest PPE alternatives<br>• Showing documentation of the costs of accidents and injuries associated with failure to use PPE |
| Cluster 3 (Moderate Criticality) | F03 | • Providing explanations and examples of the time costs of incidents and ensuring adequate time for PPE use and installation<br>• Letting workers know they will be evaluated more favorably if they work safely than if they work quickly but unsafely |
| | F09 | • Emphasizing the costs of safety incidents associated with PPE non-compliance<br>• Ensuring that field leadership understands that safety cannot be sacrificed and providing rewards and incentives for good safety performance |
| Cluster 4 (Moderate to Low Criticality) | F14 | • Ensuring that all employees are trained to the same standard<br>• Developing a strong temporary worker program and partnership with staffing agencies |
| | F13 | • Improving PPE availability by introducing technologies such as PPE vending machines and QR codes to make PPE distribution more efficient<br>• Improve PPE funding by obtaining available grants and allocating PPE pay items within the contracts of smaller subcontractors |
| | F12 | • Ensuring safety programs are up to date, post safety programs at all job sites, and communicate OSHA PPE requirements<br>• Enforcing PPE compliance and creating a sliding scale for safety performance penalties |
| Cluster 5 (Low Criticality) | F16 | • Implementing multi-language literature and training (e.g., using images and pictures in training)<br>• Fostering an inclusive workplace culture |
| | F07 | • Encouraging and rewarding positive peer pressure around PPE use<br>• Discouraging negative peer pressure via effective field monitoring and education |

that a high proportion of construction incidents are a result of unsafe behavior (i.e., human error) should be reconsidered. Unsafe behavior should be deemed as the direct cause of incidents, and it is a result of root causes such as lack of upper management support, safety personnel incompetence, and inadequate safety supervision. Addressing the root causes is critical to reduce unsafe behavior.

On the practical level, this study will eventually contribute to reducing fatal and nonfatal incidents among construction workers. The study helps decision makers better manage and engineer critical contributing factors to PPE non-compliance by prioritizing the allocation of available resources (e.g., safety allocated funds and competent safety personnel). Specifically, factors clustering enables decision makers to focus on the most critical factors by utilizing provided proactive measures. The suggested proactive measures call for actions from all stakeholders (i.e., PPE designers and manufacturers, upper management, safety personnel, frontline supervisors, and workers). The proactive measures focus on leadership and frontline supervisor accountability; safety resources, including adequate PPE supply; communication; safety policies; specialized training for wearing PPE in adverse conditions; worker attitudes; gaining worker input on PPE; leadership involvement and visibility; emphasizing the financial and reputational stakes of PPE non-compliance; PPE alternatives for individuals with health problems; case-by-case decision making; and multilanguage literature and training, including pictures. These areas of focus fall within upper management and safety personnel's control. Accordingly, the overall study findings suggest that the root causes of PPE non-compliance are embedded within the actions of upper management and safety personnel. The top three most important proactive measures for PPE compliance are to encourage, measure, and monitor frontline accountability; to emphasize the stakes associated with not using PPE; and to provide more resources to field personnel and smaller construction firms. Specific suggestions for these measures include involving frontline supervisors and workers in decision making and buy-in for safety rules and investments in safety improvements, providing real world examples of the physical and financial consequences of PPE non-compliance, and providing more training and better PPE. Emphasizing the stakes of non-compliance include reminding workers that they have families waiting for them at home, having one-on-one conversations with workers about the potential consequences of their violations, showing images of and telling stories about previous incidents, and highlighting the costs of incidents (in terms of financial and time/productivity loss) to both workers and frontline supervisors.

The limited resources available for smaller construction firms, especially residential construction firms, was thoroughly discussed during the focus group sessions. Specific suggestions for providing more resources include seeking out and consulting with trade-specialized safety experts, developing partnerships, seeking grants, and providing a variety of specialized equipment by owners and general contractors, such as adjustable PPE, PPE vending machines, and worker-specific QR codes to monitor equipment distribution. These suggestions will help improve the noticeable low levels of safety culture (i.e., low upper management commitment and low safety personnel competency) that was found by Al-Bayati (2021a). On the other hand, project owners and general contractors should consider allocating a dollar amount for safety programs when hiring smaller construction firms and including a safety plan in the contract selection criteria. Owners and general contractors should realize that the cost of safety programs and equipment is hidden within project overhead. Thus, allocating a dollar amount for it in the contract is a good practice to ensure a common understanding of the safety management team and plan. Better safety management improves overall project delivery in terms of budget, time, and quality. Safety issues can lead to work interruptions and undesirable press. Thus, it is to the owner's benefit to allocate funds for safety.

Finally, providing rewards and incentives for good safety performance was suggested to address the undesirable influence of performance pressure (being on time within the project schedule). This suggestion aims to integrate safety performance into overall firm operations. Safety management is often viewed as a non-core business obligation to prevent OSHA fines (Ladewski & Al-Bayati, 2019). Thus, integrating safety into business functioning is crucial. Construction practitioners should be aware that OSHA discourages rewards and incentives that may lead to non-reporting of injuries and near misses. Therefore, it is recommended to provide incentives and rewards for employees who frequently report near misses and unsafe conditions and behavior, as well as those who actively participate in safety training and safety talks.

## 4. Limitations

The results reported in this paper should be utilized in light of two main limitations. First, the criticality assessment employs a cross-sectional survey. Although the study findings are sufficient to draw inferences, as they were validated utilizing focus groups, there is a need for field observations to further validate the study findings. Specifically, the low score of the peer pressure factor could be a result of the survey methodology. Participants who are asked about the influence of peer pressure may tend to report low scores. The low scoring could be explained by a phenomenon termed "social desirability," which is the tendency to respond to questions in the manner that is likely to be most socially approved (Davis, 2010). People tend to reject that their peers may influence their behavior. Furthermore, the social proof phenomenon should also be assessed, which is different from peer pressure in that it is self-motivated. Within this study context, the social proof suggests that if lots of workers are not wearing or inappropriately wearing PPE, then other workers believe that there is a good reason for such behavior and will follow the same behavior. Social proof was first assessed and discussed by Milgram et al. (1969). Second, the causal interrelations among the 16 factors were not assessed. It is anticipated that some factors are a result of one or more of the others. Thus, it is recommended that future research focus on the causal interrelations between the identified factors.

## 5. Conclusion

This study delivers a comprehensive review of the factors that contribute to PPE non-compliance on construction worksites. This study included three phases: (1) identification of PPE non-compliance factors, (2) criticality risk assessment, and (3) findings validation and practical recommendations. Accordingly, 16 factors were identified through an extensive literature review. The identified factors were grouped into four categories (design factors, safety climate factors, safety culture factors, and other factors). Furthermore, a criticality assessment was conducted to rank the factors based on their anticipated influence on PPE non-compliance. Finally, separate strategies to reduce the undesirable effects of each factor were provided. The identified factors, the criticality assessment, and the suggested strategies must be realized and purposefully implemented by upper management and safety personnel to reduce PPE non-compliance in construction workplaces. Accordingly, this study contributes significantly to the knowledge surrounding construction practices.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsr.2023.02.008.

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