Hazard Perception and Rainy-Weather Safety Mitigation in Construction: A Predictive PLS-SEM Model from Malaysia

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DOI: https://doi.org/10.47772/IJRISS.2026.101000386

Received: 20 October 2026; Accepted: 25 October 2026; Published: 03 November 2026

ABSTRACT

Rainfall-related hazards can disrupt construction safety through both physical site exposure and operational or human-factor mechanisms, yet limited research has examined how these hazards translate into practical mitigation responses. This study develops and tests a predictive model of Rainy-Weather Safety Mitigation (RWSM) among construction practitioners in Malaysia. A quantitative cross-sectional survey involving 128 respondents was analysed using partial least squares structural equation modelling (PLS-SEM). Two reflective hazard constructs; Site Exposure and Physical Hazards (SEPH) and Operational and Human-Factor Hazards (OHFH), were modelled alongside Formal Rainy-Weather Safety Planning and Accident Experience as predictors of a formative RWSM composite. The measurement model demonstrated satisfactory reliability, convergent validity, and discriminant validity. Structural results showed that SEPH was positively associated with RWSM ($\beta = .350$, $p = .001$), followed by OHFH ($\beta = .297$, $p = .006$), whereas Formal Planning ($\beta = .028$, $p = .691$) and Accident Experience ($\beta = -.111$, $p = .561$) were not significant predictors. The model explained 36.4% of the variance in RWSM. Predictive assessment further indicated positive out-of-sample relevance ($Q^2_{\{predict\}}=.256$), while CVPAT confirmed significantly lower predictive loss than the benchmark ($p = .001$). The findings suggest that rainy-weather safety mitigation is more closely associated with practitioners' recognition of current physical and operational hazards than with formal planning or prior accident experience alone, highlighting the need for hazard-responsive and implementation-oriented safety management in tropical construction.

Keywords: rainfall-related hazards; construction safety; hazard perception; rainy-weather mitigation; PLS-SEM

INTRODUCTION

Construction work is highly sensitive to environmental conditions because a substantial proportion of site activities is performed outdoors and under continuously changing physical conditions. Rainfall can alter ground stability, surface friction, visibility, access conditions, equipment operation, electrical exposure, and the coordination of workers and plant. These effects are particularly important in tropical environments, where rainfall is a recurrent site condition rather than an exceptional event. Previous construction-weather research has established that precipitation can disrupt task feasibility, labour productivity, equipment operation, and project

schedules, but much of this literature has treated weather primarily as a source of delay or productivity loss rather than as a trigger for safety-management response (Schuldt et al., 2021)(Refaie et al., 2020). This distinction is important because a construction activity may remain technically feasible during rain while simultaneously becoming less safe to perform.

The emerging climate–occupational-safety literature reinforces the need to move beyond purely productivity-oriented interpretations of adverse weather. (Baek & Choi, 2026), in a recent practitioner-informed study of construction workers, showed that climate-related occupational risks arise through interconnected environmental, health, organisational, and managerial pathways. Their findings emphasised weather-contingent scheduling, managerial capacity, education, and coordinated workplace protection rather than fragmented responses to individual hazards. Similarly, (Azmi & Misnan, 2026) concluded that research integrating climate resilience and worker-focused construction safety remains limited, particularly in Malaysia, despite growing exposure to heavy rainfall, heat, and other climate-related stressors. These recent studies show that the research problem is shifting from simply identifying climatic hazards towards understanding how organisations and workers respond to them.

This shift is consistent with broader developments in construction-safety research. Hazard recognition and risk perception have increasingly been treated as central mechanisms linking site conditions to safety behaviour. (Sun et al., 2025), in a systematic review of 232 construction hazard-recognition and risk-perception studies, identified risk perception as a major component in explaining risky behaviour and developing effective safety-management strategies, while also highlighting continuing research gaps in worker-centred and developing-country contexts. Recent empirical studies likewise demonstrate that safety behaviour depends not only on formal rules but also on how hazards, management actions, supervision, training, and behavioural control are perceived. (Man et al., 2025), for example, found that safety supervision and training influenced construction workers' safety behaviour largely through behavioural and perceptual mechanisms, rather than through simple direct relationships. These findings suggest that the presence of a safety mechanism does not necessarily guarantee an equivalent operational response.

The distinction between formal safety arrangements and actual mitigation response is particularly relevant to rainy-weather construction. Formal plans may specify responsibilities, inspection procedures, work-suspension criteria, protective equipment, or emergency actions, but their practical effectiveness ultimately depends on whether these provisions are translated into field-level measures. Construction-safety research increasingly recognises this implementation problem. (Zhang et al., 2024) showed that different safety-management measures exert heterogeneous effects on worker safety behaviours, with some management dimensions producing stronger and more stable effects than others. Thus, it cannot be assumed that the existence of a formal safety plan necessarily corresponds to stronger implementation of specific mitigation measures. This issue becomes especially important under rapidly changing rainfall conditions, where immediate decisions about personal protective equipment, work suspension, temporary shelter, communication, and coordination may be required.

The Malaysian context provides additional justification for investigating this hazard–response relationship. Malaysia's Occupational Safety and Health (Construction Work) (Design and Management) Regulations 2024, which came into force on 1 June 2024, strengthened the regulatory emphasis on proactive safety and health management throughout construction projects (Manusia, 2024). This preventive orientation implies that weather-related risks should be anticipated and managed systematically rather than addressed only after accidents or operational failures occur. At the same time, Malaysia's tropical construction environment exposes projects to recurrent rainfall and associated site-condition changes. Recent Malaysian climate-safety research has consequently called for more explicit integration of climate-related hazards into construction planning and safety management (Azmi & Misnan, 2026).

Earlier phases of the present research programme have begun to address this issue empirically. The first study examined rainfall-related construction-site conditions and found that rainfall occurrence, operational disruption, deteriorating site conditions, and drainage preparedness formed a strongly interconnected site-level construct among Malaysian practitioners (Radzuan, Othman, Zakariah, et al., 2026). The second study moved specifically into safety and identified two related but distinguishable rainfall-related hazard dimensions: Site Exposure and Physical Hazards (SEPH) and Operational and Human-Factor Hazards (OHFH). SEPH represented hazards such

as slippery surfaces, unstable ground, work at height, flooding, and inadequate rainy-condition PPE, whereas OHFH captured reduced visibility, electrical hazards, machinery performance, worker alertness, and communication or coordination difficulties (Radzuan, Othman, Musa, et al., 2026). These findings established that rainfall-related construction safety is multidimensional rather than a single undifferentiated risk domain.

However, identifying hazard dimensions does not establish whether those hazards are associated with stronger safety responses. This constitutes the principal gap addressed by the present study. Existing construction-weather research largely explains exposure and disruption, while construction-safety research more commonly examines hazard recognition, safety behaviour, training, supervision, or safety climate. Comparatively little empirical research has connected rainfall-specific hazard perceptions directly to the implementation of rainy-weather mitigation measures, particularly within tropical construction. The distinction is important because risk identification and risk response are conceptually different stages of safety management. A practitioner may recognise a hazard without corresponding controls being implemented, while some organisations may implement mitigation proactively even in the absence of previous accident experience.

A second gap concerns the roles of formal planning and previous accident experience. Conventional safety logic would suggest that a formal rainy-weather plan should strengthen mitigation and that previous exposure to accidents may stimulate organisational learning and preventive action. Yet contemporary construction-safety evidence cautions against assuming such direct relationships. Management measures can influence behaviour differently depending on organisational and behavioural mechanisms (Zhang et al., 2024), while recent safety-behaviour research shows that supervision and training frequently operate through attitudes, perceived control, and other intermediate processes (Man et al., 2025). It therefore remains an empirical question whether formal rainy-weather planning and accident experience are actually associated with stronger mitigation practices.

Accordingly, this study develops and tests a predictive model of Rainy-Weather Safety Mitigation (RWSM) in Malaysian construction. The model examines whether SEPH and OHFH are associated with stronger mitigation response and whether formal rainy-weather safety planning and previous accident experience provide additional explanatory value. RWSM is operationalised through practical field responses, including wet-weather protective measures, suspension of high-risk activities, temporary shelter or covered access provision, and rainfall-related safety briefings. Rather than treating these actions as interchangeable reflections of a single underlying attitude, the study conceptualises them collectively as a mitigation composite representing distinct but complementary safety responses. The study makes three contributions. First, it advances rainfall-related construction research from hazard identification towards hazard–response modelling, addressing how recognised safety hazards are associated with practical mitigation. Second, it distinguishes between physical/site-exposure hazards and operational/human-factor hazards, allowing their independent relationships with mitigation response to be assessed. Third, it evaluates the relative roles of hazard perception, formal planning, and accident experience while also examining the model's out-of-sample predictive capability using PLS-SEM. In doing so, the study responds to recent calls for more integrated, worker-centred, and climate-responsive safety management in construction and provides evidence relevant to tropical construction environments where rainfall-related risks must be managed as recurring operational conditions rather than exceptional events.

LITERATURE REVIEW

2.1 From rainfall-related hazard recognition to safety mitigation

Construction safety research has increasingly shifted from treating hazards as purely physical conditions toward examining how workers and organisations perceive, interpret, and respond to those hazards. This transition is important because the presence of a hazard does not automatically produce a preventive response. Hazard recognition involves identifying a potentially unsafe condition, whereas risk perception concerns the perceived likelihood and severity of harm; both may subsequently influence safety-related decisions and behaviours. A recent systematic review by (Sun et al., 2025), covering 232 studies on construction hazard recognition and risk perception, concluded that hazard recognition and risk perception are closely connected with risk-taking behaviour and safety-management outcomes. The review also identified a need for more worker-centred research and greater attention to developing-country contexts.

Empirical research similarly shows that recognising danger is only one element in a broader cognitive–behavioural process. (Mastrantonio et al., 2024), studying construction workers' occupational risk perception, found that perceptions of injury risk were associated with beliefs about inadequate prevention measures and other risk-related factors. Their findings also suggested that workers may underestimate occupational risks even when the hazards themselves are objectively well established. This distinction is especially relevant under rainy conditions. A worker or supervisor may recognise slippery ground, deteriorating visibility, or machinery-related difficulties without necessarily activating the corresponding mitigation measures.

The present study therefore adopts a hazard–response perspective, in which perceived rainfall-related hazards are treated as potential antecedents of rainy-weather safety mitigation. This reasoning is consistent with broader safety-cognition research. (Han et al., 2022) argued that workers' safety awareness and sense of danger influence the behavioural decision-making process and that external conditions interact with safety cognition when workers decide whether to act safely or unsafely. Their analysis also drew on protection-motivation reasoning, according to which perceived danger can stimulate protective behaviour when the threat is recognised and an effective response is available.

However, a hazard–response relationship should not be assumed to be automatic. Recent construction-safety research demonstrates that organisational and behavioural mechanisms can alter how perceived risks are translated into action. (Man et al., 2025), for example, found that safety supervision and safety training did not directly influence behavioural intention but operated substantially through attitudes, subjective norms, and perceived behavioural control. Similarly, (Zhang et al., 2024) showed that different safety-management measures exert heterogeneous effects on different safety behaviours rather than producing uniform responses. These findings indicate that safety response is best viewed as the outcome of interacting perceptual, organisational, and contextual mechanisms.

This issue becomes especially important in the context of climate-related construction hazards. (Baek & Choi, 2026) found that effective protection of construction workers against climate-related risks requires coordinated workplace measures, including weather-contingent scheduling, managerial capacity, education, policy integration, rest facilities, and protective technologies. Their study emphasised that fragmented or isolated responses are unlikely to provide sufficient worker protection. Thus, rainy-weather safety management should similarly be understood as a coordinated response to multiple, interconnected hazards rather than as a reaction to a single isolated condition.

The previous phase of the present research programme identified two empirically distinct but related dimensions of rainfall-related construction safety: Site Exposure and Physical Hazards (SEPH) and Operational and Human-Factor Hazards (OHFH). SEPH captured direct physical exposures such as slippery surfaces, unstable ground, work at height, flooding, and inadequate rainy-condition PPE, whereas OHFH represented reduced visibility, electrical hazards, equipment and machinery performance, worker concentration, and communication or coordination problems. The two dimensions were positively related but remained empirically distinguishable, supporting a multidimensional interpretation of rainfall-related construction safety (Radzuan, Othman, Musa, et al., 2026).

2.2 Site Exposure and Physical Hazards and rainy-weather safety mitigation

SEPH represents hazards that are directly observable within the physical construction environment. Rainfall can produce wet working surfaces, unstable or saturated ground, localised flooding, and difficult conditions for working at height. Such hazards differ from more latent organisational or psychological concerns because they are often immediately visible to workers and supervisors. Physical changes in the work environment may therefore provide strong cues for implementing protective action. The construction-safety literature provides a strong rationale for expecting such a relationship. Risk-perception research has consistently shown that workers make behavioural decisions partly on the basis of how strongly they perceive immediate danger. (Sun et al., 2025) identified hazard recognition and risk perception as central research domains in explaining construction risk-taking and safety behaviour, while also noting that hazard-recognition failures remain an important contributor to unsafe decisions. (Mastrantonio et al., 2024) likewise found that construction workers' risk perceptions were associated with their assessments of preventive deficiencies and occupational danger.

The relevance of direct environmental exposure is heightened under adverse weather conditions. (Baek & Choi, 2026) reported that climate-related construction hazards can generate both direct physical risks and indirect accident-related effects and argued that protection requires workplace strategies that respond to changing environmental conditions. Their qualitative evidence included concerns associated with flooding, ground collapse, and electrical accidents during extended monsoon conditions. These findings reinforce the view that visible deterioration of the work environment should stimulate safety-management responses. From a hazard–response perspective, increasing perceptions of slippery surfaces, unstable ground, flooding, work-at-height exposure, and insufficient protective measures should therefore be associated with stronger mitigation actions. Such actions may include enhanced PPE use, suspension of high-risk work, temporary access or shelter provision, and specific safety briefings. The proposed relationship does not imply that perception itself causes mitigation; rather, stronger perceived physical exposure is expected to be associated with greater reported mitigation response.

2.3 Operational and Human-Factor Hazards and rainy-weather safety mitigation

Not all rainfall-related construction hazards are manifested through visible physical conditions. Rainfall can also affect how work is performed and coordinated by reducing visibility, affecting equipment performance, interacting with electrical systems, impairing worker concentration, and making communication more difficult. These conditions constitute the Operational and Human-Factor Hazards (OHFH) dimension established in the preceding rainfall-safety study (Radzuan, Othman, Musa, et al., 2026). The inclusion of operational and human factors is consistent with contemporary construction-safety research, which increasingly recognises that unsafe outcomes emerge from interactions among environmental, technological, organisational, and behavioural conditions. (Zhang et al., 2024) demonstrated that different management interventions influence different categories of worker safety behaviour to varying degrees, suggesting that construction safety cannot be effectively managed through a single uniform intervention. (Man et al., 2025) similarly showed that safety supervision, training, coworker support, attitudes, subjective norms, and perceived behavioural control interact when shaping safety behaviour. Rainfall may intensify these interactions. Reduced visibility may affect hazard detection and vehicle movement; machinery performance may deteriorate under wet conditions; electrical systems may become more difficult to manage safely; and communication between workers and supervisors may become increasingly important when work activities need to be interrupted or resequenced. (Baek & Choi, 2026) emphasised that climate-related worker protection depends on coordinated organisational action rather than isolated technical measures. This argument is directly relevant to OHFH because many of its components require active coordination and operational decision-making rather than purely physical engineering controls. The hazard-recognition literature also supports the expectation that heightened perception of operational danger should be associated with stronger safety responses. (Sun et al., 2025) concluded that risk perception contributes to the development of safety-management strategies and influences how workers respond to unsafe conditions. From this perspective, practitioners who perceive stronger operational and human-factor difficulties during rainfall should also report stronger mitigation measures designed to maintain safe work performance.

2.4 Formal rainy-weather safety planning and mitigation response

Formal safety planning represents the organisational attempt to convert general safety objectives into defined procedures, responsibilities, and response mechanisms. Within rainy-weather construction, a formal plan may specify monitoring arrangements, work-suspension criteria, responsibilities for drainage and access management, PPE requirements, communication channels, and emergency procedures. In principle, such planning should create a more structured basis for implementing mitigation measures. Construction-safety literature generally supports the importance of systematic management arrangements. (Sun et al., 2025), based on a large multidimensional assessment of safety-management interventions, found that objectives and assessments, safety organisation, and hazard and emergency management produced some of the strongest and most stable effects on safety behaviour. Likewise, safety-climate research increasingly indicates that organisational systems, supervision, training, and management support shape the context in which workers make safety-related decisions. (Man et al., 2025) found that safety supervision and training significantly influenced core psychological determinants of construction workers' safety behaviour, even when some direct relationships with behavioural intention were nonsignificant. Recent climate-related construction research also stresses the importance of formal and coordinated workplace strategies. (Baek & Choi, 2026) identified policy integration,

climate-specific regulatory standards, weather-contingent scheduling, organisational investment, and enhanced managerial capacity as central elements of workplace protection against climate hazards. This evidence provides a theoretical basis for expecting formal rainy-weather safety planning to support mitigation implementation. However, the relationship should not be assumed to be straightforward. Formalisation and implementation represent different organisational processes. A site may possess written procedures that are weakly enforced, poorly communicated, inadequately resourced, or insufficiently adapted to changing site conditions. (Zhang et al., 2024) found that the effects of safety-management measures vary substantially across specific behaviours, demonstrating that improving a management dimension does not guarantee an equally strong effect on all safety outcomes. Similarly, (Man et al., 2025) showed that organisational interventions can operate indirectly through psychological mechanisms rather than producing immediate behavioural effects. Therefore, while the expected theoretical relationship is positive, empirical examination remains necessary, particularly for rainfall-specific safety planning where research evidence is still limited.

2.5 Accident experience and rainy-weather safety mitigation

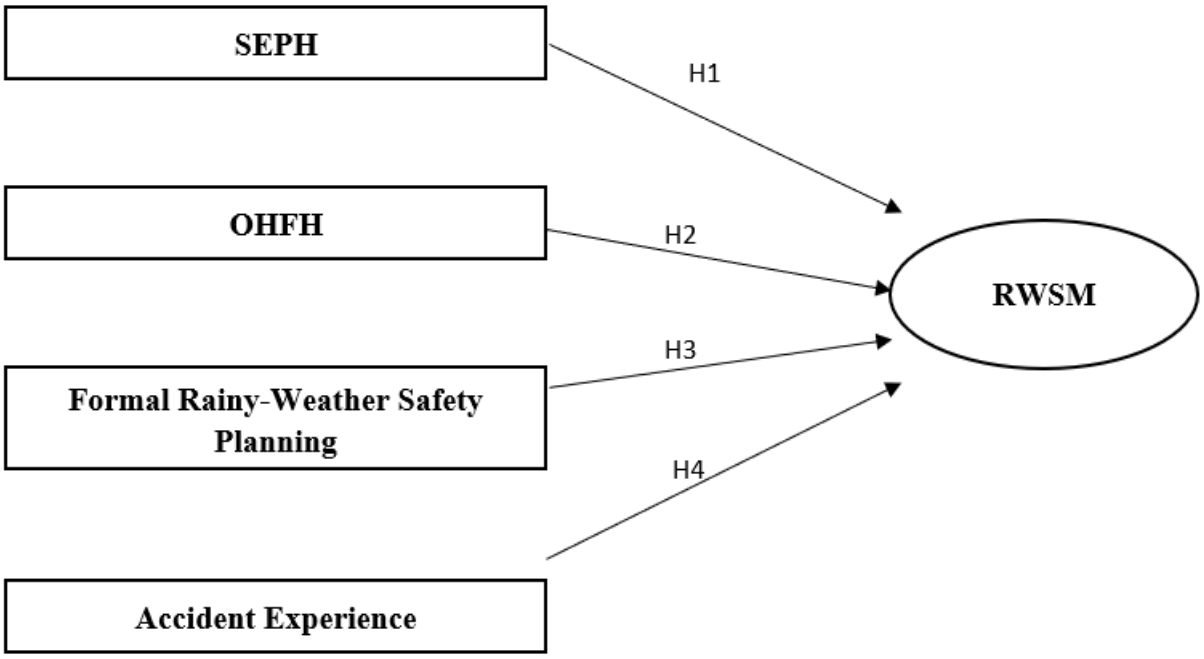
Accident experience represents another potential source of safety learning. Direct involvement in or exposure to an accident may heighten perceptions of vulnerability, increase awareness of the consequences of unsafe conditions, and encourage subsequent preventive behaviour. Social cognitive reasoning further suggests that individuals can learn both from direct experience and from observing the experiences of others. Recent construction research provides evidence that accident experience can influence safety cognition and behaviour, but the relationship is more complex than a simple learning effect. (Yang et al., 2025) examined direct and indirect accident experience among construction workers and found that both forms were associated with lower unsafe behaviour. Indirect experience had the stronger effect and operated partly through risk perception, safety attitude, and safety competence. This suggests that accident experience may influence later behaviour through cognitive interpretation rather than through exposure alone. Recent evidence by (Alruqi et al., 2026),based on a survey of 252 multinational construction workers in Saudi Arabia, further highlights the importance of safety training in influencing workers' safety behaviour. The findings revealed that safety training significantly improved safety compliance but did not significantly influence safety participation. Individual responsibility partially mediated the relationship between safety training and safety compliance, while nationality did not significantly moderate the relationships examined. These findings suggest that safety training alone may be insufficient to encourage proactive safety participation, highlighting the need to strengthen individual responsibility and implement additional organisational strategies to promote effective safety behaviour among construction workers. The wider literature also suggests that accident experience can affect the way workers interpret subsequent risks. (Mastrantonio et al., 2024) found that construction workers' perceptions of injury risk were associated with seniority and beliefs regarding danger, prevention deficiencies, behaviour, and unpredictable events. Earlier occupational research has likewise indicated that prior accident experience can influence risk perception, although organisational factors such as safety climate and leadership may exert equally or more important influences (Oah et al., 2018). These mixed findings create a strong justification for testing accident experience independently rather than assuming that accident exposure necessarily translates into more effective mitigation. In the context of rainy-weather construction, workers or practitioners who have previously experienced an accident may be more attentive to protective measures, but the extent to which this experience is converted into site-level mitigation may depend on organisational learning, management response, and the type or severity of the accident. The theoretical expectation remains that prior accident experience should encourage preventive response.

CONCEPTUAL FRAMEWORK

The proposed model positions RWSM as the principal endogenous construct and examines four antecedents: SEPH, OHFH, Formal Rainy-Weather Safety Planning, and Accident Experience. SEPH and OHFH represent distinct rainfall-related hazard domains previously identified empirically, while Formal Planning captures the organisational preparedness dimension and Accident Experience represents experiential learning.

Conceptually, the model distinguishes three sources of safety response. The first is current hazard perception, represented by SEPH and OHFH. The second is organisational formalisation, represented by Formal Rainy-

Weather Safety Planning. The third is experiential learning, represented by Accident Experience. The distinction is theoretically important because safety actions may arise from immediate recognition of site conditions, from organisational systems, or from previous exposure to adverse events. Existing research shows that these mechanisms can influence safety behaviour differently and may not operate with equal strength (Zhang et al., 2024).



This framework extends rainfall-related construction-safety research beyond hazard identification by explicitly examining the transition from hazard perception to mitigation response. It also provides a basis for evaluating whether practical rainy-weather mitigation is more strongly associated with immediate hazard recognition, formal organisational planning, or previous accident experience. Accordingly, the hypothesised model are therefore:

H1: Site Exposure and Physical Hazards (SEPH) are positively associated with Rainy-Weather Safety Mitigation (RWSM).

H2: Operational and Human-Factor Hazards (OHFH) are positively associated with Rainy-Weather Safety Mitigation (RWSM).

H3: Formal Rainy-Weather Safety Planning is positively associated with Rainy-Weather Safety Mitigation (RWSM).

H4: Previous accident experience is positively associated with Rainy-Weather Safety Mitigation (RWSM).

METHODOLOGY

3.1 Research design and analytical context

This study employed a quantitative cross-sectional research design to examine how rainfall-related construction hazards are associated with rainy-weather safety mitigation among construction practitioners in Malaysia. The analysis used an existing survey dataset comprising 128 valid responses from personnel representing technical, managerial, supervisory, safety, and operational construction roles. The original survey was administered voluntarily, and respondents were informed of the study purpose before participation. Responses were analysed in aggregate form without personally identifying information. The present study constitutes a distinct analytical extension of earlier work using the same respondent sample. The preceding study focused on identifying and validating the underlying dimensional structure of rainfall-related safety hazards and established two related but

distinguishable dimensions: Site Exposure and Physical Hazards (SEPH) and Operational and Human-Factor Hazards (OHFH). In contrast, the present study addresses a different research question by examining whether these hazard dimensions, together with formal rainy-weather safety planning and previous accident experience, explain and predict Rainy-Weather Safety Mitigation (RWSM). This distinction was maintained to avoid reproducing the exploratory objectives of the earlier analysis. Because the present analysis uses an already established dataset, the analytical sample was fixed at $N = 128$ rather than being prospectively determined specifically for this structural model. Accordingly, the traditional "10-times rule" was not used to justify sample adequacy, as contemporary PLS-SEM guidance considers this rule imprecise and recommends power-oriented approaches such as the inverse-square-root method instead (Kock & Hadaya, 2018).

3.2 Constructs and measurement

The model incorporated five constructs: SEPH, OHFH, RWSM, Formal Rainy-Weather Safety Planning, and Accident Experience. SEPH and OHFH were specified using the item groupings established in the preceding exploratory-factor analysis. SEPH comprised C1, C3, C5, C7, and C9, representing direct exposure to rainfall-related physical site hazards. OHFH comprised C2, C4, C6, C8, and C10, representing operational and human-factor concerns associated with rainy conditions. The ten hazard indicators were originally measured using five-point Likert-type response scales. SEPH and OHFH were specified as reflective measurement models (Mode A) because their indicators were treated as manifestations of the respective underlying hazard dimensions. Reflective measurement is appropriate where variation in the underlying construct is expected to be reflected in its indicators, whereas formative measurement is appropriate when indicators jointly form the conceptual meaning of a construct (Hair & Alamer, 2022)(Joseph F. Hair et al., 2022). RWSM was operationalised using four mitigation indicators, D4–D7, covering complementary rainy-weather safety responses such as protective measures, suspension of high-risk activities, temporary shelter or protected access, and rainfall-related safety briefings. RWSM was specified as a formative composite (Mode B) because these mitigation measures represent distinct management actions that collectively constitute the overall mitigation response rather than interchangeable manifestations of one underlying trait. In formative specification, indicators may contribute unequally to the composite and need not exhibit the high inter-item correlations expected from reflective scales. Current PLS-SEM guidance recommends Mode B weighting for such formative measurement models. Two additional exogenous variables were modelled as single-item constructs. D3, Formal Rainy-Weather Safety Planning, was retained on its original 1–5 response scale rather than being dichotomised, thereby preserving the full information contained in respondents' ratings. D1, Accident Experience, was retained using its original questionnaire coding. Single-item constructs were not subjected to internal-consistency reliability assessment because Cronbach's alpha, composite reliability, and AVE require multiple indicators.

3.3 Rationale for using PLS-SEM

Partial Least Squares Structural Equation Modelling (PLS-SEM) was selected because the objective of the study was both explanatory and predictive, and because the proposed model combines reflective and formative/composite measurement. PLS-SEM is particularly suitable when prediction is an explicit research objective, when formative constructs are included, and when the focus extends beyond parameter estimation toward out-of-sample predictive assessment (Hair & Alamer, 2022). The analysis was performed using SmartPLS 4 (Sarstedt et al., 2024). The analytical procedure followed the recommended sequence of assessing the measurement models first, followed by evaluation of the structural model and, finally, the model's predictive performance (Joseph F. Hair et al., 2022).

3.4 Assessment of the reflective measurement models

The reflective measurement properties of SEPH and OHFH were assessed in terms of indicator reliability, internal consistency, convergent validity, and discriminant validity. Indicator reliability was evaluated using outer loadings, with loadings of approximately .708 or higher considered desirable because this indicates that the construct explains approximately 50% or more of the indicator variance. Indicators with lower loadings were not to be removed mechanically; theoretical relevance, composite reliability, and AVE were considered jointly before making any deletion decision (Joseph F. Hair et al., 2022). Internal consistency reliability was assessed using, Cronbach's alpha, composite reliability (rho_C), and reliability coefficient (rho_A). Values between

approximately .70 and .95 were considered satisfactory. Convergent validity was evaluated using the average variance extracted (AVE), with AVE ≥ .50 indicating that the construct explains at least half of the variance of its indicators. Discriminant validity between SEPH and OHFH was evaluated using the heterotrait-monotrait ratio of correlations (HTMT). HTMT was preferred over the traditional Fornell-Larcker criterion because simulation research has shown that HTMT is more sensitive in detecting discriminant-validity problems (Henseler et al., 2015). An HTMT value below .90 was used as the principal criterion for establishing empirical distinctiveness between the two reflective constructs.

3.5 Assessment of the formative RWSM composite

Because RWSM was specified formatively, its evaluation followed criteria different from those applied to SEPH and OHFH. Cronbach's alpha, composite reliability, and AVE were therefore not used to evaluate RWSM. The formative assessment proceeded in two stages. First, indicator collinearity was evaluated using outer variance inflation factor (VIF) values. Low VIF values indicate that the formative indicators provide sufficiently distinct information and that their estimated weights are not distorted by excessive collinearity. Second, the outer weights of D4–D7 were evaluated to determine their relative contribution to RWSM. Statistical significance of the formative weights was assessed using bootstrapping. Where an outer weight was nonsignificant, the indicator's absolute contribution, represented by its outer loading, and its theoretical relevance were considered before any removal decision. This approach is important because a formative indicator may have a nonsignificant relative weight but still provide conceptually important information that should be retained to preserve content validity (Joseph F. Hair et al., 2022).

3.6 Structural model assessment and hypothesis testing

Following satisfactory assessment of the measurement models, the structural model was evaluated for collinearity, path significance, explanatory power, and effect size. Inner VIF values were first examined to determine whether substantial collinearity existed among SEPH, OHFH, Formal Planning, and Accident Experience as predictors of RWSM. Structural relationships were then assessed using standardised path coefficients (beta). Statistical inference was based on a non-parametric bootstrapping procedure. For the final analysis, a large bootstrap sample was used to obtain standard errors, *t*-statistics, *p*-values, and confidence intervals for the estimated coefficients. Current SmartPLS guidance recommends approximately 10,000 bootstrap subsamples for final inference because a large number of resamples increases the stability of the bootstrap estimates. Hypotheses were evaluated at a significance level of ($p < .05$). The magnitude and direction of the standardised path coefficients were interpreted alongside statistical significance rather than relying solely on *p*-values. The explanatory performance of the model was evaluated using the coefficient of determination: R^2 for RWSM and the corresponding adjusted (R^2). The contribution of each predictor to the endogenous construct was additionally examined using (f^2) effect sizes. Following conventional guidelines, values around .02, .15, and .35 were interpreted respectively as small, medium, and large effects, although these thresholds were treated as approximate rather than rigid decision rules.

3.7 Out-of-sample predictive assessment

Because the study was explicitly designed as a hazard-to-response predictive model, structural significance and (R^2) alone were considered insufficient for model evaluation. Out-of-sample prediction was therefore assessed using PLSpredict and the cross-validated predictive ability test (CVPAT). PLSpredict employs *k*-fold cross-validation to generate predictions for observations that are not used in model estimation, thereby providing an assessment of generalisation beyond the estimation sample (Shmueli et al., 2019). Predictive relevance was examined using: $Q^2_{predict}$, root mean square error (RMSE), and mean absolute error (MAE). Positive ($Q^2_{predict}$) values were interpreted as evidence that the PLS-SEM model predicts better than a naïve mean-based benchmark. Prediction errors from PLS-SEM were also compared with those obtained from a linear-model benchmark, with lower PLS-SEM RMSE or MAE values indicating superior predictive performance. CVPAT was additionally applied because it provides a formal inferential test of whether the proposed PLS model achieves significantly lower out-of-sample predictive loss than benchmark predictions. This procedure strengthens prediction-oriented PLS-SEM evaluation by moving beyond descriptive comparisons of prediction errors (Sharma et al., 2023).

3.8 Ethical considerations and analytical transparency

Participation in the original survey was voluntary, respondents were informed of the research purpose, and no personally identifying information was collected. Data were treated confidentially and reported only in aggregated form. Because the same dataset has supported earlier publications, analytical transparency was maintained by clearly differentiating the present research objective from the preceding studies. The earlier papers focused on rainfall-related construction-site conditions and the exploratory identification of rainfall-related safety-hazard dimensions, whereas the present study uses those established constructs to test new structural and predictive relationships with rainy-weather mitigation. No claim is made that the present PLS-SEM analysis constitutes independent external validation of the SEPH and OHFH measurement structures; rather, the constructs were re-estimated within the new structural model and their measurement properties reassessed before hypothesis testing.

RESULTS AND ANALYSIS

The PLS-SEM analysis was conducted in three sequential stages: assessment of the reflective measurement models, assessment of the formative RWSM composite, and evaluation of the structural model and its out-of-sample predictive performance. Consistent with recommended PLS-SEM procedures, reflective constructs were evaluated using indicator loadings, internal consistency reliability, convergent validity, and discriminant validity, whereas the formative construct was evaluated primarily through collinearity, outer weights, and indicator relevance (Hair et al., 2022).

4.1 Reflective measurement model

The reflective measurement model comprised Site Exposure and Physical Hazards (SEPH) and Operational and Human-Factor Hazards (OHFH). All indicator loadings exceeded .70. For SEPH, loadings ranged from .820 to .874, while OHFH loadings ranged from .763 to .882. These results indicate satisfactory indicator reliability, as values above approximately .70 imply that a substantial proportion of indicator variance is explained by the corresponding construct. Internal consistency reliability was also satisfactory. OHFH achieved Cronbach's α = .876, ρA = .891, and ρC = .909, while SEPH recorded α = .907, ρA = .918, and ρC = .930. All reliability coefficients exceeded the recommended .70 threshold without exceeding .95, indicating satisfactory internal consistency without obvious indicator redundancy. Convergent validity was likewise established, with AVE values of .668 for OHFH and .727 for SEPH, both exceeding the .50 criterion.

Table 1. Reflective measurement model assessment

Construct	Indicators	Loading range	Cronbach's α	ρA	ρC	AVE
OHFH	C2, C4, C6, C8, C10	.763–.882	0.876	0.891	0.909	0.668
SEPH	C1, C3, C5, C7, C9	.820–.874	0.907	0.918	0.93	0.727

Discriminant validity was evaluated using the heterotrait-monotrait ratio (HTMT), which is recommended for determining whether reflectively measured constructs are empirically distinct (Henseler et al., 2015). The HTMT value between SEPH and OHFH was .746, below both the conservative .85 threshold and the more liberal .90 criterion. The two rainfall-related hazard constructs therefore demonstrated satisfactory discriminant validity. The low associations of D1 and D3 with SEPH and OHFH in the HTMT output also indicated little empirical overlap; however, because Accident Experience and Formal Planning were modelled as single-item constructs, internal-consistency statistics were not applicable to these variables.

4.2 Formative measurement assessment of RWSM

Rainy-Weather Safety Mitigation (RWSM) was specified as a formative composite comprising D4–D7. Because formative indicators jointly define rather than reflect a construct, evaluation focused on indicator collinearity and the significance and relevance of outer weights rather than Cronbach's alpha or AVE (Hair et al., 2022). The outer VIF values for D4–D7 ranged from 1.791 to 2.147, remaining well below the value of 3 commonly used to indicate potentially problematic collinearity. Thus, no evidence of critical collinearity was found among the

four mitigation indicators. Bootstrapping showed that D4 had the largest and statistically significant formative weight (w = .501, t = 2.217, p = .027). D5 (w = .330, p = .197), D6 (w = .091, p = .669), and D7 (w = .304, p = .263) had nonsignificant relative weights. Nevertheless, their absolute outer loadings remained .818, .637, and .796, respectively, indicating meaningful absolute associations with the RWSM composite. Accordingly, D5–D7 were retained because they represent conceptually distinct aspects of rainy-weather mitigation and contribute to the content domain of the formative construct. In formative measurement, nonsignificant relative weights do not necessarily justify indicator deletion when indicators remain conceptually relevant and demonstrate meaningful absolute contributions (Hair et al., 2022).

Table 2. Formative measurement assessment of RWSM

Indicator	Outer loading	Outer weight	VIF	*t*	*p*	Decision
D4	0.86	0.501	2.024	2.217	0.027	Retained
D5	0.818	0.33	2.147	1.291	0.197	Retained
D6	0.637	0.091	1.791	0.428	0.669	Retained
D7	0.796	0.304	2.084	1.119	0.263	Retained

4.3 Structural model assessment

Before examining the hypothesised relationships, collinearity among the structural predictors was evaluated. Inner VIF values ranged from 1.013 to 1.842, specifically 1.055 for Accident Experience, 1.013 for Formal Planning, 1.835 for OHFH, and 1.842 for SEPH. These values were below the recommended threshold of 3, indicating that structural collinearity was not a concern. The structural model explained 36.4% of the variance in RWSM (R^2 = .364), with an adjusted R^2 of .344. Thus, the four predictors collectively accounted for a meaningful proportion of variation in rainy-weather safety mitigation, while also indicating that additional organisational and project-level factors remain outside the present model. The hypothesis-testing results are summarised in Table 3.

Table 3. Structural model and hypothesis testing

Hypothesis	Relationship	β	*t*	*p*	f^2	Decision
H1	SEPH → RWSM	0.35	3.414	0.001	0.105	Supported
H2	OHFH → RWSM	0.297	2.769	0.006	0.075	Supported
H3	Formal Planning → RWSM	0.028	0.398	0.691	0.001	Not supported
H4	Accident Experience → RWSM	−.111	0.582	0.561	0.004	Not supported

SEPH had a positive and statistically significant relationship with RWSM (β = .350, t = 3.414, p = .001), supporting H1. This was the numerically strongest structural relationship in the model. OHFH was also positively and significantly associated with RWSM (β = .297, t = 2.769, p = .006), providing support for H2. In contrast, Formal Rainy-Weather Safety Planning showed a very small and nonsignificant relationship with RWSM (β = .028, t = 0.398, p = .691). H3 was therefore not supported. Previous Accident Experience was likewise unrelated to RWSM (β = −.111, t = 0.582, p = .561), resulting in rejection of H4. Because this coefficient was nonsignificant, its negative sign should not be interpreted as evidence of a negative substantive relationship. Effect-size analysis further showed that SEPH made the largest incremental contribution to RWSM (f^2 = .105), followed by OHFH (f^2 = .075). Both were below the conventional .15 benchmark for a medium effect and therefore represented small effects. In comparison, Accident Experience (f^2 = .004) and Formal Planning (f^2 = .001) contributed negligible incremental explanatory value.

4.4 Out-of-sample predictive performance

Because the purpose of the model extended beyond explanation to prediction, its out-of-sample predictive performance was evaluated using PLSpredict and CVPAT, in line with recommendations that PLS-SEM models should be assessed for predictive performance rather than relying solely on in-sample R^2 values (Shmueli et al., 2019)(Sharma et al., 2023). All four RWSM indicators produced positive ($Q^2_{predict}$) values. Positive ($Q^2_{predict}$)

values indicate that the model has predictive relevance relative to a naïve benchmark. Furthermore, the PLS-SEM RMSE and MAE values were lower than the corresponding linear-model (LM) errors for all four RWSM indicators. For example, the PLS-SEM RMSE for D4 was 1.060 compared with 1.181 for the LM benchmark, while for D7 the corresponding values were .925 and 1.050.

Table 4. PLSpredict assessment

Indicator	$Q^2_{\{predict\}}$	PLS-RMSE	LM-RMSE	PLS-MAE	LM-MAE
D4	0.226	1.06	1.181	0.869	0.91
D5	0.203	1.125	1.283	0.882	0.964
D6	0.116	1.031	1.132	0.843	0.89
D7	0.187	0.925	1.05	0.761	0.809

At the latent-variable level, RWSM achieved $Q^2_{\{predict\}}$ = .256, RMSE = .873, and MAE = .663, further supporting predictive relevance. The CVPAT results provided an additional inferential assessment of predictive performance. The PLS model generated a predictive loss of 1.080, compared with 1.323 for the indicator-average benchmark. The average loss difference was −.243, and this difference was statistically significant, $t = 3.483$, $p = .001$. Following (Sharma et al., 2023), the significantly lower predictive loss indicates that the proposed structural model achieved superior out-of-sample predictive performance relative to the benchmark. Overall, the prediction-oriented analyses therefore corroborated the structural findings: the model not only explained a meaningful proportion of variation in RWSM but also demonstrated evidence of generalisable predictive capability.

Summary of hypothesis testing

Of the four hypothesised relationships, two were supported. SEPH and OHFH were both positively associated with RWSM, whereas Formal Rainy-Weather Safety Planning and previous Accident Experience were not statistically significant predictors. SEPH exhibited the numerically strongest structural relationship and the largest effect size. The model explained 36.4% of the variance in RWSM and demonstrated positive out-of-sample predictive relevance through PLSpredict and statistically superior predictive performance through CVPAT. The results therefore provide empirical support for the core hazard–response proposition underlying the study: rainfall-related physical and operational/human hazard perceptions are associated with mitigation response, whereas formal planning and prior accident experience alone do not explain meaningful additional variation in mitigation within the present sample.

DISCUSSION

The present study extends rainfall-related construction-safety research from hazard identification to hazard–response modelling by examining whether two previously established rainfall-related hazard dimensions, Site Exposure and Physical Hazards (SEPH) and Operational and Human-Factor Hazards (OHFH) are associated with Rainy-Weather Safety Mitigation (RWSM). The structural model produced a clear pattern. Both SEPH and OHFH were positively and significantly associated with mitigation response, whereas Formal Rainy-Weather Safety Planning and Accident Experience were not significant predictors. Collectively, the model explained 36.4% of the variance in RWSM and also demonstrated meaningful out-of-sample predictive performance. These findings suggest that practical rainy-weather safety responses may be more closely connected to practitioners' recognition of current site and operational hazards than to previous accident exposure or formal planning alone.

5.1 Rainfall-related hazard perception and mitigation response

The finding that both SEPH and OHFH significantly predicted RWSM provides empirical support for the central hazard–response proposition of the study. SEPH was positively associated with RWSM ($\beta = .350$, $p = .001$), while OHFH also showed a significant positive relationship ($\beta = .297$, $p = .006$). Thus, practitioners who reported stronger rainfall-related safety concerns also tended to report stronger implementation or endorsement of

mitigation measures. This result is broadly consistent with contemporary construction-safety research emphasising the role of hazard recognition and risk perception in shaping safety-related behaviour. (Sun et al., 2025), in a systematic review of construction hazard recognition and risk perception research, concluded that these cognitive processes are closely connected to risk-taking behaviour and the development of effective safety-management strategies. A wider systematic review of high-risk occupations similarly found that most studies reported a positive association between risk perception and safer behaviour, although the strength of this relationship varies according to contextual and psychological factors. The present findings extend this reasoning into the specific context of rainy-weather construction by showing that both physical-site hazards and operational/human-factor hazards are associated with stronger mitigation responses. However, the results should not be interpreted to mean that hazard perception automatically produces mitigation. The cross-sectional research design establishes association rather than temporal or causal ordering. It is equally plausible that organisations with stronger safety-management practices make workers more aware of hazards, producing higher hazard ratings and stronger mitigation responses simultaneously. This possibility is important because recent evidence shows that safety behaviour is shaped by interacting organisational and psychological mechanisms rather than by a single linear pathway. (Man et al., 2025), for example, found that safety supervision, coworker support, and training influenced construction workers' safety behaviour through attitudes, subjective norms, and perceived behavioural control. Thus, the present hazard–response relationships are best interpreted as evidence of a meaningful association that warrants longitudinal or intervention-based testing rather than as proof of causality.

5.2 Site Exposure and Physical Hazards as the strongest predictor

SEPH exhibited the numerically strongest structural relationship with RWSM (β = .350), together with the largest effect size among the four predictors (f^2 = .105). OHFH followed with β = .297 and f^2 = .075. Although the difference between the two path coefficients was not formally tested and should therefore not be described as statistically significant, the pattern suggests that directly observable physical site hazards may provide particularly salient cues for mitigation. This interpretation is plausible because SEPH captures conditions that are readily visible or physically experienced during rainfall, including slippery surfaces, unstable ground, work at height, flooding, and deficiencies in rainy-condition protection. The previous study using the same respondent sample established these indicators as a coherent physical/site-exposure dimension distinct from operational and human-factor concerns. Physical deterioration can often demand an immediate operational decision: work areas may need to be isolated, high-risk activities suspended, access routes managed, or protective equipment deployed. In contrast, some operational or human-factor hazards, such as reduced concentration or communication difficulty may be less immediately visible and may require more deliberate monitoring or supervisory recognition. The pattern is also compatible with recent climate-related construction research. (Baek & Choi, 2026) found that climate hazards affecting construction workers require coordinated organisational protection, including weather-contingent scheduling, managerial action, worker education, and appropriate protective technologies. Importantly, their findings indicate that effective climate-risk management requires practical workplace responses rather than fragmented acknowledgement of environmental exposure. The present study adds a rainfall-specific quantitative dimension to this argument: stronger perceptions of physical rainfall-related hazards were associated with more extensive mitigation response. Nevertheless, the relatively small effect size for SEPH (f^2 = .105) indicates that physical hazard perception alone is not sufficient to explain mitigation. This is theoretically important. The results suggest that visible hazard exposure may stimulate safety response, but implementation is likely to depend also on organisational resources, management commitment, project constraints, work sequencing, client requirements, regulatory pressure, and safety climate. Future studies should therefore avoid reducing rainy-weather mitigation to a simple perception–response mechanism.

5.3 Operational and human-factor hazards as an independent source of safety response

The significant OHFH → RWSM relationship (β = .297, p = .006) provides an important complement to the SEPH result. Rainy-weather safety management is therefore not associated solely with visible physical conditions. Practitioners' concerns regarding reduced visibility, electrical risks, equipment and machinery performance, worker concentration, and communication or coordination also contribute independently to mitigation response. This finding is relevant because traditional adverse-weather management can become overly focused on tangible engineering controls such as drainage, PPE, temporary shelter, or surface treatment. While such measures are necessary, they may not address the operational and human processes through which

rainfall affects safety. Reduced visibility, for example, can interfere with plant–worker interaction and hazard detection; equipment problems may require altered work sequencing or inspection; and communication difficulties may become particularly important when rainfall causes rapid changes in access, task feasibility, or work-suspension decisions. Construction-safety literature increasingly supports such a multidimensional view. (Zhang et al., 2024) found that different safety-management measures exert different effects across types of worker safety behaviour, with objectives and assessment, safety organisation, and hazard and emergency management among the more stable influences. Similarly, recent evidence on construction safety training suggests that effective interventions must address not only procedural knowledge but also hazard recognition, engagement, and behavioural application. These findings reinforce the present study's implication that rainy-weather mitigation should combine physical controls with operational coordination, communication, equipment management, and attention to human performance. The independent significance of OHFH after SEPH was included in the same model is particularly important. It indicates that the operational/human dimension contributes information beyond that provided by physical site exposure. This supports retaining the two-dimensional conceptualisation developed in the previous study rather than collapsing all rainfall-related hazards into a single general safety score.

5.4 Formal planning and the possible planning–implementation gap

Contrary to H3, Formal Rainy-Weather Safety Planning was not significantly associated with RWSM ($\beta = .028$, $t = 0.398$, $p = .691$), and its effect size was essentially negligible ($f^2 = .001$). The use of the original 1–5 D3 response scale is important here because it preserves the full variation in respondents' perceptions of formal planning. Thus, the nonsignificant relationship cannot readily be attributed to information loss from dichotomising the variable. At first sight, this result appears inconsistent with the expectation that formal safety planning should strengthen implementation. Construction-safety literature generally emphasises organisational arrangements, emergency management, supervision, training, and structured procedures as important influences on safety performance (Zhang et al., 2024)(Man et al., 2025). Climate-related construction research likewise emphasises weather-contingent scheduling, policy integration, managerial capacity, and comprehensive workplace response plans. However, the finding may point to an important distinction between formalisation and implementation. Having—or perceiving that the site has—a formal rainy-weather safety plan does not necessarily mean that the procedures are actively translated into wet-weather PPE, work suspension, protected access or shelter, and safety briefings. Safety documentation may exist primarily to satisfy organisational or regulatory requirements, while field implementation can depend on supervisory commitment, resources, project pressures, communication, and the immediacy of site hazards. (Zhang et al., 2024) similarly demonstrated that safety-management measures do not affect all safety behaviours uniformly. Therefore, the absence of a direct Formal Planning → RWSM relationship may reflect a planning–implementation gap rather than evidence that formal planning lacks value. This interpretation should nevertheless remain cautious. D3 is a single-item perceptual measure, and it cannot capture the quality, completeness, enforcement, frequency of review, or implementation maturity of rainy-weather planning. A site with a brief generic procedure and a site with detailed weather-trigger thresholds, assigned responsibilities, inspection protocols, and work-suspension rules could receive similar respondent ratings. Consequently, the present study cannot conclude that formal safety plans are ineffective. A more defensible conclusion is that perceived formal planning alone did not explain additional variation in mitigation after rainfall-related hazard perceptions were considered. Future studies should therefore operationalise formal rainy-weather planning as a multi-item construct covering plan existence, clarity of trigger criteria, assignment of responsibilities, monitoring arrangements, communication procedures, resource availability, drills, and enforcement. Such a design could determine whether planning quality rather than the simple perception of planning predicts mitigation.

5.5 Accident experience and the limits of reactive learning

H4 was also unsupported. Previous Accident Experience was not significantly associated with RWSM ($\beta = -.111$, $p = .561$), and its effect size was negligible ($f^2 = .004$). The negative coefficient should not be interpreted substantively because the relationship was statistically nonsignificant. The absence of a significant relationship challenges a simple reactive-learning assumption in which exposure to an accident automatically leads to stronger subsequent prevention. In practice, accident experience may generate learning only when organisations investigate incidents effectively, communicate lessons, revise procedures, and convert experience into

operational controls. Individual exposure alone may therefore be insufficient. This interpretation is consistent with broader safety research showing that safety learning depends on more than exposure to adverse events. Construction safety interventions can influence behaviour through training, supervision, attitudes, and perceived control rather than through experience alone. Furthermore, recent hazard-recognition research emphasises that effective safety behaviour depends on how danger is recognised and interpreted, not simply on whether a worker has previously encountered an accident. The result has an important preventive implication: rainy-weather safety systems should not depend on accidents occurring before stronger controls are activated. If hazard perception itself is associated with mitigation, organisations should strengthen anticipatory recognition and response mechanisms through inspections, weather monitoring, toolbox discussions, and predefined intervention thresholds. This aligns with contemporary climate-risk approaches that advocate proactive and coordinated protection rather than reactive measures following harmful events. Again, measurement limitations should be acknowledged. Accident Experience was represented by a single item and did not distinguish severity, recency, accident type, direct versus witnessed experience, or whether organisational learning followed the event. These characteristics could moderate the relationship between accident experience and subsequent mitigation and warrant more detailed measurement in future research.

5.6 Composition of rainy-weather safety mitigation

The formative measurement results provide additional insight into how RWSM is constructed. D4 had the largest and only statistically significant formative weight (w = .501, p = .027), whereas the weights of D5, D6, and D7 were nonsignificant. Nevertheless, the corresponding absolute loadings remained meaningful (.818, .637, and .796), supporting retention of all four indicators to preserve the conceptual coverage of mitigation. The result suggests that the D4 mitigation activity makes the strongest relative contribution within this sample, but it should not be interpreted as evidence that the remaining mitigation practices are unnecessary. Formative indicators represent non-interchangeable components; removing a practice because its relative weight is nonsignificant could narrow the substantive meaning of RWSM. This is especially relevant for rainy-weather safety, where mitigation is likely to require a package of controls rather than a single intervention. Recent climate-safety research reinforces this interpretation. (Baek & Choi, 2026) explicitly argue that effective protection of construction workers from climatic hazards requires integrated organisational, technological, educational, and policy actions rather than isolated measures. Similarly, systematic research on construction safety training shows that learning effectiveness depends on the design and delivery of interventions rather than merely their presence. Thus, the formative specification of RWSM is substantively appropriate: PPE-related measures, suspension of high-risk activities, shelter or protected access, and safety briefings represent complementary rather than substitutable responses.

5.7 Explanatory and predictive performance of the model

The structural model explained 36.4% of the variance in RWSM (R^2 = .364; adjusted R^2 = .344). This represents meaningful explanatory power for a behavioural and organisational outcome, but also shows that a substantial proportion of mitigation variation remains unexplained. The finding is therefore more useful when interpreted as evidence of partial explanation rather than as a comprehensive model of rainy-weather safety response. Likely omitted determinants include safety climate, management commitment, regulatory pressure, resource availability, project type, project size, construction stage, client requirements, contractual arrangements, availability of weather information, and supervisory competence. Incorporating such variables could substantially improve subsequent models. Importantly, the study went beyond in-sample explanation by assessing out-of-sample prediction. All RWSM indicators showed positive $Q^2_{\{predict\}}$ values, and PLS-SEM produced lower RMSE and MAE values than the linear-model benchmark for all four indicators. At construct level, $Q^2_{\{predict\}}$ was .256. These findings satisfy the basic logic of PLSpredict, which emphasises assessment of model performance on observations outside the estimation sample rather than relying solely on explanatory indices such as R^2 (Shmueli et al., 2019). The CVPAT result further showed that the PLS model had significantly lower predictive loss than the benchmark (average loss difference = −.243, t = 3.483, p = .001). CVPAT was developed specifically to determine whether a PLS-SEM model achieves significantly superior out-of-sample predictive accuracy relative to a benchmark, thereby adding inferential evidence to predictive assessment (Sharma et al., 2023). The combination of positive $Q^2_{\{predict\}}$, lower indicator-level prediction errors, and significant CVPAT performance therefore provides stronger support for the model than the structural

coefficients alone. Nevertheless, predictive success should not be overstated. Prediction is demonstrated for the variables and population represented in the present sample; external validation using a separate dataset remains necessary before claiming broad generalisability across Malaysian construction projects or other tropical countries.

5.8 Theoretical contribution: moving from hazard identification to hazard–response modelling

The study contributes theoretically by moving rainfall-related construction-safety research beyond the identification and ranking of hazards. Previous work with the same dataset established that rainy-weather hazards could be organised into the SEPH and OHFH dimensions. The present results show that these two dimensions are not merely descriptive categories: both are significantly associated with practical mitigation response. This leads to a broader hazard–response perspective in which rainy-weather safety management can be understood through three potential pathways: current hazard recognition, organisational formalisation, and experiential learning. Within the present model, only the first pathway represented by SEPH and OHFH received empirical support. Formal planning and previous accident experience did not add significant explanatory value. This pattern refines rather than contradicts existing safety-management theory. Recent construction literature increasingly treats safety behaviour as the outcome of interactions among hazard perception, organisational systems, training, supervision, and behavioural cognition. The present study adds rainfall-specific evidence showing that immediate perceptions of physical and operational/human risks may be more closely associated with mitigation than formal plans or previous accidents considered in isolation. The implication is not that planning and experience are theoretically unimportant, but that their effects may be indirect, contingent, or implementation-dependent. Formal planning could, for example, improve hazard recognition, which then prompts mitigation, while accident experience could influence risk perception or organisational learning rather than mitigation directly. Such mediation mechanisms could be investigated in future studies using richer multi-item constructs and longitudinal data.

5.9 Practical interpretation

From a managerial perspective, the results indicate that rainy-weather safety management should focus on strengthening the conversion of hazard recognition into field-level action. Physical signs such as slippery surfaces, unstable ground, flooding, and unsafe work-at-height conditions should activate predefined responses. At the same time, supervisors should monitor less visible operational and human-factor risks such as visibility, machinery performance, electrical exposure, worker alertness, and communication. The nonsignificant Formal Planning result is particularly relevant for practice. Construction organisations should avoid equating the existence of a rainy-weather safety procedure with effective implementation. Formal plans should contain measurable activation criteria, assigned responsibilities, inspection requirements, communication protocols, and clear work-suspension or resequencing triggers. This interpretation is consistent with evidence that construction safety-management measures differ in their effectiveness and that organisational systems need to be linked to specific behaviours and actions. Similarly, the nonsignificant accident-experience relationship suggests that organisations should not wait for incidents to generate preventive action. Rainfall-responsive safety should be proactive and anticipatory, consistent with recent recommendations for coordinated climate-related workplace protection in construction. Overall, the findings support a shift from a documentation-centred or accident-reactive approach toward an active hazard-recognition and response approach. The central practical message is therefore not simply that construction sites need more rainy-weather rules, but that they need systems capable of recognising changes in physical and operational conditions and translating those changes into timely safety actions.

CONCLUSION

This study developed and tested a predictive hazard–response model of rainy-weather safety mitigation in Malaysian construction. By integrating Site Exposure and Physical Hazards (SEPH), Operational and Human-Factor Hazards (OHFH), Formal Rainy-Weather Safety Planning, and previous Accident Experience within a PLS-SEM framework, the study moved beyond identifying rainfall-related hazards to examine how those hazards are associated with practical mitigation response. The findings showed that both rainfall-related hazard dimensions were significant predictors of RWSM. SEPH exhibited the strongest relationship ($\beta = .350$, $p = .001$),

followed by OHFH (β = .297, p = .006). In contrast, Formal Planning (β = .028, p = .691) and Accident Experience (β = −.111, p = .561) did not significantly explain mitigation response. The model accounted for 36.4% of the variance in RWSM, while PLSpredict and CVPAT provided additional evidence of out-of-sample predictive relevance. These results indicate that rainy-weather safety response is more closely associated with practitioners' recognition of current physical and operational/human hazards than with formal planning or previous accident exposure considered independently. The findings should not be interpreted as diminishing the importance of planning or organisational learning. Rather, they highlight that plans and experience must be translated into actionable field-level controls before they can influence mitigation. The study therefore contributes a hazard–response perspective to rainfall-related construction safety. Effective management of rainy conditions requires more than identifying weather hazards or maintaining written procedures; it requires systems capable of recognising changing site and operational conditions and converting those signals into timely protective action. For tropical construction environments such as Malaysia, this implies integrating physical-site controls with equipment management, communication, worker monitoring, flexible activity sequencing, and clearly defined intervention thresholds. Future independent and longitudinal studies incorporating objective rainfall and safety-performance data are required to validate and extend the proposed model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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