FRAMEWORK FOR IMPLEMENTATION OF SMART PERSONAL PROTECTION EQUIPMENT FOR HIGH-RISK MAINTENANCE TASKS IN HIGH-RISE BUILDINGS

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Abstract. In the modern built environment industry, smart technology is increasingly used for building operations and maintenance. However, there remains a significant lag in the integration of smart technologies into health and safety practices, particularly in relation to Personal Protective Equipment (PPE). Consequently, a significant number of accidents and damages occur due to the absence of PPE during High-Risk Maintenance Tasks (HRMTs) in High-Risk Buildings (HRBs), largely because of practical challenges associated with the general use of PPE. Therefore, this research focuses on the implementation of Smart Personal Protective Equipment (SPPE) for HRMTs in high-rise buildings. To achieve the study's objectives, a qualitative research approach was used. To gather the required data, first, a case study is conducted, followed by structured and expert interviews. The collected data is then analysed manually using content analysis. The findings of this study revealed that HRMTs in HRBs in Sri Lanka predominantly involve confined space operations, work at height, hot works, medium voltage electrical maintenance and all of which pose substantial safety hazards. The integration of Smart Personal Protective Equipment (SPPE) demonstrates strong potential to mitigate these limitations through concurrent monitoring, hazard detection and efficient communication. Accordingly, a conceptual framework was developed, offering a systematic and practical guideline for effective SPPE implementation in HRBs, to improve occupational safety performance, worker compliance, and operational efficiency within the Sri Lankan construction-built environment context.

Keywords. *Smart Personal Protective Equipment (SPPE), High Risk Maintenance Tasks (HRMTs), High Rise Buildings (HRBs), Hazards, Strategies*

1. Introduction

According to the National Fire Protection Association (2022), a high-rise building (HRB) is defined as any structure exceeding 330 feet (approximately 100 meters) in height measured from the lowest level of fire department vehicle access to the floor of the highest occupied story or any building containing more than 20 stories. Low-rise buildings are typically defined as structures with fewer than four storeys and relatively simple access for maintenance, whereas high-rise buildings exceed this scale and involve complex systems and vertical risks (Abbood et al., 2021). From a health and safety perspective, high-rise buildings are more critical due to increased exposure to work-at-height hazards, system complexity, and emergency challenges, which significantly elevate maintenance risks compared to low-rise buildings (Abbood et al., 2021; Craighead, 2009). Accordingly, the study places greater emphasis on high-rise buildings as opposed to low-rise buildings. Key categories of High Risk Maintenance Tasks (HRMTs) in HRB are confined space works such as (Air Handling Unit (AHU), diesel tank, chiller, elevator maintenance), hot works (welding and grinding), works at height (Gondola – façade cleaning and painting, pipe repairing, works), works involve with electrical equipment (HT panel, switch board, transformer maintenance) and works involve in using dangerous substance (pest control, fogging treatment, condenser and chilled water and corrosion cleaning) (Udani et al., 2016). The critical threats, or sudden accidents during maintenance tasks to maintenance workers can be mitigated by wearing appropriate general Personal Protective Equipment (PPE) when performing such High-Risk Maintenance Tasks (HRMTs) (Weissman, 2018). Proving the importance of PPE, previous studies indicate that occupational diseases and health issues are more common among maintenance employees mainly because of a lack of PPEs (Lind, 2018; Nyjusta, 2017). Therefore, Factories Ordinance No. 45 of 1942 established regulations to protect the health, safety, and welfare of those employed in factories and other establishments to specify the legal requirements for providing effective and suitable PPE, such as screens, shields, goggles or spectacles, as necessary when performing maintenance works (Pallewaththa et al., 2018).

PPE is defined in the UK Regulations as 'something meant to be worn or carried by an individual at work that shields him from one or more threats to his health or safety' (United Kingdom, 1992). Moreover, the provision of PPE is regarded as the last resort in the hierarchy of hazard control measures for workers (Zhou et al., 2014).

One of the prevailing critical issues concerning the use of PPE is that, even though organizations mandate the use of personal protective equipment (PPE), ground-level workers often remain reluctant to wear it (Delpachitra & Allis, 2022). Providing reasons for this issue, McPherson and Donna (2008) and Kimberly-Clark Professional (2007), in their study on PPE compliance within a particular organization, reported that 62% of respondents were unwilling to wear PPE due to discomfort. The main causes cited were excessive heat, poor fit, and unpleasant appearance.

As a solution, Márquez-Sánchez et al. (2021) stated that smart technology is increasingly integrated into PPE in developed and industrialized countries, where advanced digital safety systems and wearable technologies are widely adopted, to address such challenges. These are referred to as Smart Personal Protective Equipment (SPPE), which has been identified as a promising solution to overcome the limitations of conventional PPE (Gonzalez-Cortes et al., 2020). Smart Personal Protective Equipment (SPPE), often conceptualized as part of smart wearable systems, represents an evolution of conventional PPE through the integration of advanced digital technologies such as sensors, Internet of Things (IoT) connectivity, and real-time data processing capabilities (Márquez-Sánchez et al., 2021; Svertoka et al., 2021; Umer et al., 2024). Unlike traditional PPE, which functions as a passive barrier against hazards, SPPE introduces active, adaptive, and data-driven protection mechanisms, enabling continuous environmental monitoring, physiological sensing, and instantaneous risk communication.

Previous studies highlight that conventional PPE often suffers from poor compliance due to discomfort, limited functionality, and lack of feedback mechanisms (Ammad et al., 2021; Ada et al., 2024). In contrast, SPPE addresses these limitations through ergonomic design, smart materials, and integrated communication systems, thereby improving both protection and user engagement (European Agency for Safety and Health at Work, 2020). Furthermore, SPPE facilitates other critical functions such as location tracking and emergency response coordination, which are particularly valuable in HRB maintenance (Márquez-Sánchez et al., 2021).

Despite these advantages, literature also identifies challenges (see section 2.5). The global SPPE market is projected to grow significantly from $3.13 billion in 2021 to $9.05 billion by 2028 (Chong et al., 2023), indicating its growing relevance in modern occupational health and safety management. As discussed by Zhou et al. (2021), the limited popularity of SPPE, particularly within the Sri Lankan context, can be attributed to several practical challenges encountered during its implementation in High-Risk Maintenance Tasks (HRMTs) in High-Rise Buildings (HRBs). These challenges include financial constraints (e.g., high initial investment, elevated maintenance costs, and low return on investment), technical difficulties (e.g., the need for specialized knowledge, durability concerns, and maintenance issues), legal barriers (e.g., lack of standardization and regulatory frameworks), social resistance (e.g., employee reluctance and privacy concerns), and environmental implications (e.g., the generation of electronic waste) (Yap et al., 2022). Therefore, this study aims to develop a framework for promoting the implementation of the SPPEs for HRMTs in HRBs of Sri Lanka.

2. Literature Review

2.1 HIGH RISK MAINTENANCE TASKS IN HIGH RISE BUILDINGS

Pham et al. (2025) emphasized that maintenance tasks in HRBs pose heightened risks due to the expansive areas involved, which exceed those of typical confined spaces in ordinary buildings. Their study identifies four principal causes of confined-space accidents: toxic atmospheres (e.g., hazardous pollutants or oxygen deficiency), flammable environments (explosions and fire hazards), engulfment (submersion in liquids such as water or oil), and physical injuries (including electrocution, falling objects, entrapment in equipment, or falls from height). In addition, working at height constitutes another critical hazard requiring stringent safety measures.

Hot work is another major hazard in HRB maintenance, encompassing operations that generate heat, flames, or sparks, such as welding, cutting, grinding, and chipping (Ontario, 2016). These activities are performed frequently by maintenance staff and pose multiple risks, including ignition from flying sparks, flammable debris (swarf, molten metals, slag), heat conduction through pipes, explosive atmospheres, electrical hazards, and exposure to toxic fumes and gases (Weissman, 2018). Along with hot work maintenance tasks, maintenance tasks related to the electrical system also involve other high-risk tasks (Pham et al., 2025). Moreover, the use of hazardous chemicals in cleaning, corrosion treatment, HVAC servicing, painting, sanding, blasting, and pest control introduces further dangers, ranging from acute effects (eye irritation, dizziness) to chronic, irreversible conditions such as lung disease to the workers (Loftness et al., 2007; Kelly, 2023). Maintenance workers are also frequently exposed to high noise levels in areas such as generator rooms, air-conditioning plant rooms, pump rooms, lift motor rooms, and during hot works (Palmer, 2020). Prolonged exposure to such environments can lead to occupational noise-induced hearing loss (ONIHL), a well-documented condition resulting from workplace noise (Tak et al., 2019). Collectively, these findings underscore the critical need for stringent safety protocols in HRB maintenance to mitigate both immediate and long-term occupational health risks.

2.2 CHALLENGES OF GENERAL PPEs

As discussed in the introduction, despite the availability of PPEs, its effective application remains limited by several interrelated challenges. A primary concern relates to ergonomic limitations, where prolonged use of PPE results in discomfort, poor fitting, heat stress, skin irritation, and restricted mobility, all of which negatively influence user tolerance and compliance (Ammad et al., 2021; Ada et al., 2024). These physical constraints are closely linked to behavioural outcomes, as discomfort is consistently identified, it reduces the willingness of workers to consistently wear PPE during work activities.

In addition to physical discomfort, PPE use significantly affects workplace communication and situational awareness. Equipment such as masks, helmets, and hearing protection devices can obstruct verbal communication and diminish auditory and visual cues, thereby increasing the likelihood of misunderstandings and reducing overall operational efficiency (Burgher et al., 2019). Similarly, sensory limitations caused by gloves, goggles, and face shields reduce tactile feedback and peripheral vision, which can compromise precision in task execution and elevate the risk of accidents in dynamic work environments (Márquez-Sánchez et al., 2021).

Beyond ergonomic and sensory constraints, the design related issues of PPE have also contributed to usability challenges. Conventional equipment is often characterised by bulkiness and limited adaptability, making it cumbersome during extended use and less compatible with diverse working conditions (Márquez-Sánchez et al., 2021). These design limitations are further compounded by operational and organisational factors, particularly inadequate training and low safety awareness, which result in inconsistent or incorrect usage practices among workers (Ada et al., 2024). Furthermore, maintenance and hygiene requirements impose additional burdens, as PPE requires regular cleaning, inspection, and replacement; failure to properly manage these processes can reduce protective effectiveness and increase contamination risks (Khan & Haddara, 2003).

Overall, PPE challenges are interconnected, affecting usability, compliance, and safety performance.

2.3 ADVANCEMENTS IN SPPE

To transform PPE into SPPE, it is integrated with electronic components such as sensors, detectors, batteries, and data transmission modules (Pearl et al., 2025). These enable immediate environmental monitoring, hazard detection, data processing, and adaptive response (Casini, 2022). Additionally, SPPE also encompasses advanced material-based PPE without electronics, including shock-absorbing footwear and chemically responsive gloves, which enhance comfort and protection (Saidi et al., 2021). Advancements in wearable technology, particularly the introduction of Bluetooth-enabled wireless connectivity, have significantly accelerated the development and adoption of smart safety solutions, leading to substantial growth over the past two decades (Pearl et al., 2025). Common SPPE applications include smart helmets, belts, bracelets, augmented safety glasses, airbag jackets, smart earwear, sensor-based gloves, smart knee protectors, and advanced safety boots.

2.5 EXISTING CHALLENGES FOR IMPLEMENTATION OF SPPES

Despite its technical advantages, the widespread adoption of SPPE in HRB maintenance remains constrained by multifaceted challenges, consistent with Schall et al. (2018). Financial barriers, including high initial capital investment, ongoing maintenance costs, and uncertain return on investment (ROI), remain significant obstacles, particularly for small and medium sized enterprises. In agreement with the facts presented by Mosly (2026), the results of the study confirmed the technical and operational challenges, such as system complexity, frequent updates, cybersecurity vulnerabilities, data privacy concerns, and insufficient workforce training, which further hinder the effective deployment of SPEE. According to Sammy et al. (2020), legal and regulatory gaps limit standardized certification and large-scale commercialization, while social resistance emerges from privacy concerns, employee acceptance, and potential cultural disruption. Environmental sustainability issues, notably electronic waste generation, also pose long-term concerns as per the data collection results (Bhoi et al., 2025).

3. Methodology

This study was conducted as a qualitative research investigation to identify the existing state of High-Risk Maintenance Tasks (HRMTs) in High-Rise Buildings (HRBs), associated hazards, and the potential application of Smart Personal Protective Equipment (SPPE). A comprehensive literature review was undertaken to examine HRMTs in HRBs, their occupational hazards, the practical challenges associated with conventional PPE, relevant standards and regulations, and the conceptual foundations of SPPE.

Data collection was carried out using expert interviews and case studies as research methods. In the first phase, a case study analysis was conducted on two HRBs located in the Colombo metropolitan area of Sri Lanka, where general PPE was used for HRMTs. These cases were selected using a non-probability sampling technique due to limitations in accessibility and time. In the second phase, ten (10) semi-structured interviews were conducted with industry experts (E1–T6) specializing in SPPE, HRMTs in HRBs, and occupational health and safety. The interviewees are selected using purposive/ judgemental sampling with the purpose of obtaining an expert judgment of the area studied. Accordingly, the expert interviews were conducted with professionals who possessed more than ten years of experience in the research relevant fields, ensuring the reliability and depth of the collected insights.

E1, a director, contributed 12 years of experience, while E2, also a director, possessed 10 years. E3, the Technical Manager, added 10 years of expertise. E4 and E5, serving as Chief Safety Officers, reported 20 and 18 years, respectively. E6 and E7, both Facilities Managers, each contributed 12 years. E8, the Chief Mechanical Engineer, brought 22 years, while E9 and E10, the Chief Electrical and Civil Engineers, contributed 20 years each. Collectively, these participants provided a strong foundation for analyzing SPPE adoption in HRB maintenance contexts.

The primary objectives of the semi-structured interviews were to first obtain general background information, followed by collecting specific details regarding the selected HRBs, gather in depth insights into maintenance tasks in HRBs, the currently practised conventional PPE for the identified maintenance activities, the existing challenges associated with PPE usage, and the strategies adopted to mitigate these challenges. Content analysis was conducted to analyse the gathered data from the semi structured to arrive at the findings based on the expert opinion.

4. Results and Discussion

The research methodology outlined the systematic approach adopted to address and bridge the identified research gap. Data analysis and discussion were primarily conducted in two phases, in accordance with the adopted research methodology.

- Phase 1: Two case studies
- Phase 2: Expert interviews

4.1 PHASE 1: FINDINGS OF CASE STUDY

The case study analysis was undertaken covering two HRBs, which are in Colombo, Sri Lanka. Data was captured by conducting semi-structured interviews, making observations and reviewing relevant documents. Two buildings are further named Building A and Building B.

Building A is a 43-storey commercial high-rise structure with a total height of 152 m, supported by an in-house maintenance workforce of 48 personnel. Building B is a 34-storey hotel building with a height of 129 m and an in-house maintenance team comprising 38 personnel. The selection of these buildings represents both commercial and hospitality typologies, enabling comparative analysis of operational conditions, workforce capacity, and maintenance risk exposure within high-rise built environments. Moreover, during the study, the researcher referred to relevant documents to gather data on reported accidents which are incurred when functioning HRMTs, risk assessment diagrams, SOPs and user manuals for general PPEs and training records for general PPE usage.

The responses, especially with regard to case study observation and data collection, are in percentages as follows. The Percentages were derived by dividing the number of responses reporting each challenge by the total sample, ensuring proportional representation of consensus and variation. The analytical data findings of phase 01 indicated that discomfort and fitting issues (100%) and communication difficulties (100%) are the most dominant challenges of general PPE. This is followed by monitoring and feedback issues (66.7%) and lack of technological advancement (66.7% highlighting moderate but significant operational limitations. Limited sensory perception (50%) was reported by half of the participants, while cumbersome design (33.3%) and compliance issues with lack of training (33.3%) were less frequently noted. Maintenance and hygiene issues (16.7%) were the least reported challenge. In addition, a new concern, which is bad peer influence (100%), emerged from the respondents, indicating a strong social factor affecting PPE usage behaviour in practice.

In addition to the above summary of findings, one of the respondents have stated that, "*the variety of body shapes and sizes among technicians is one of the key causes of discomfort and fitting concerns.* Furthermore, one of the technicians of case B stated that, "*due to the nature of HRMTs in HRBs frequently requires* *extended durations of workers in difficult settings such as confined places, elevated heights, or harsh temperatures."* In these situations, technicians must wear PPE for lengthy periods of time, which may cause pain and ergonomic strain. Fitting issues of PPE can compound these problems, resulting in tiredness, musculoskeletal discomfort, and lower productivity among technicians. Thereby, the most critical challenge that could be identified was discomfort and fitting issues in general PPEs.

Communication difficulties were also highlighted by all interviewees as a challenge. Accordingly, an interviewee has claimed *that "Many traditional PPE solutions, such as helmets, respirators, and ear protection, are intended to give maximum protection against physical risks, but they may inadvertently impede communication by covering the face, lips, or ears."* Thereby, a technician from case A said that *"Face masks or respirators, for example, used by technicians conducting operations like painting, welding, or chemical handling can muffle voice and confuse facial expressions, making it difficult for team members to hear orders or effectively communicate critical information."* Similarly, helmets with built-in ear protection can reduce external noises and impair verbal communication, especially in noisy or congested work conditions. Along with communicational challenges, the interviewees have also emphasized the lack of situational awareness of ground level workers while performing HRMTs.

As another challenge, it has been claimed that "*Monitoring and feedback pose significant challenges to the use of general PPE in HRMTs within HRBs."* Another Interviewee T6 has stated that *"One of the most significant issues in monitoring PPE usage for HRMTs in HRBs is a lack of appropriate technology and tools for real-time tracking and compliance evaluation."* Therefore, they further have suggested to *probe on wearable sensors, RFID tags, and IoT-enabled devices, which have the potential to improve monitoring capabilities by giving concurrent data on PPE usage, location, and condition, to reduce the monitoring efficiency.* However, they have also expressed that the application of such technologies necessitates large expenditures in infrastructure, training, and data management systems, which may be too expensive for certain businesses.
Additionally, respondents argued that "*all technicians who are recruited by both building A and B are from authorized technical institutes*". Within those institutes, they provide considerable training for handling and maintaining general PPEs to mitigate workplace hazards for the students. Accordingly, after finalizing the respective course, they have almost all the knowledge about the general PPEs. Therefore, this challenge is not raised.
Almost all technicians claimed that *"Maintenance and hygiene are not significant challenges for the usage of general PPE for high-rise maintenance technicians in HRBs".*

A new challenge that was added by the respondents was that the bad peer influence can have an impact on technicians' risk perceptions and willingness to utilize PPEs correctly

4.2 PHASE 2: FINDINGS OF EXPERT INTERVIEWS

The expert interviews indicated that smart personal protective equipment (SPPE) can strongly solve the limitations of conventional PPE in HRMTs within HRBs.

From a socio-technical systems perspective, the Experts also stated that key limitations of general personal protective equipment (PPE) in Sri Lankan high-rise building maintenance (HRMT) include discomfort and poor fit, communication barriers, limited sensory perception, cumbersome design, low compliance, inadequate monitoring, and hygiene concerns, which reflect a misalignment between human factors and technological design. Drawing on expert interviews, Smart Personal Protective Equipment (SPPE) is identified as a technologically integrated intervention that systematically resolves these constraints through ergonomic and digital augmentation.

In relation to physical and ergonomic constraints, SPPE, incorporating adaptive padding, lightweight composites, breathable fabrics, and thermal regulation systems directly mitigate discomfort and fitting issues, thereby improving sustained user acceptance and work endurance. Communication barriers and limited sensory perception are addressed through IoT-enabled sensors and augmented reality (AR) interfaces, which enhance real-time hazard recognition, spatial awareness, and task guidance in complex HRMT environments.

Furthermore, cumbersome design and poor compliance are reduced through human-centred engineering and wearable optimization, improving usability and behavioural adoption, consistent with the Technology Acceptance Model (TAM), where perceived ease of use and usefulness drive compliance behaviour. Monitoring and feedback limitations are resolved through embedded biometric sensors and cloud-based analytics, enabling continuous physiological tracking, fatigue detection, and supervisory intervention. Hygiene-related risks are mitigated through antimicrobial coatings and self-cleaning material technologies, enhancing long-term occupational health outcomes.

In addition, SPPE enhances operational coordination through integrated hands-free, noise-cancelling communication systems, while AR-based training and predictive maintenance functions improve procedural compliance, skill acquisition, and system reliability. These integrated capabilities collectively demonstrate SPPE as a socio-technical upgrade rather than a replacement of PPE, enhancing human–technology interaction in HRMT operations.

However, consistent with Schall et al. (2018), Mosly (2026), Sammy et al. (2020), and Bhoi et al. (2025), adoption remains constrained by financial, technical, regulatory, social, and environmental barriers. These include high capital investment, system complexity, cybersecurity vulnerabilities, lack of standardised certification, user resistance, and electronic waste concerns.

Moreover, to address these constraints, experts propose phased implementation through pilot projects, rental-based deployment models, bulk procurement strategies, and cloud-integrated systems to reduce initial financial burden. Technical barriers can be mitigated through structured training frameworks, user-friendly interfaces, and cybersecurity governance protocols. Regulatory gaps require proactive institutional engagement and standard development, while social resistance can be reduced through participatory implementation, transparent data governance, and workforce engagement strategies. Collectively, these measures position SPPE as a scalable, adaptive, and sustainable intervention for improving safety performance and operational efficiency in Sri Lankan HRMT contexts.

5. The Conceptual Framework

Accordingly, the results of both the case studies and expert interviews validated the previously identified challenges and strategies for SPPE implementation, while also eliminating certain issues and revealing new potential problems that may arise during SPPE usage. Based on existing literature knowledge, refined through data collection and study findings, Figure 1 was created to present a framework that provides clear guidance for the implementation of SPPE in HRMTs within HRBs.

The proposed framework for Smart Personal Protective Equipment (SPPE) implementation can be practically adapted to Sri Lanka’s high-rise building maintenance sector by aligning technological innovation with regulatory, cultural, and infrastructural realities. As per the initial start according to the framework, needs assessment should begin with task-specific risk identification in local HRBs, incorporating worker feedback to address discomfort, communication barriers, and compliance gaps. Selection and customization of SPPE must consider affordability, durability under tropical climatic conditions, and compatibility with existing safety practices. Implementation planning should integrate phased adoption supported by government incentives, organizational funding, and reliable connectivity infrastructure. Deployment requires structured training programs, awareness campaigns, and stakeholder engagement to overcome resistance and enhance acceptance. Continuous monitoring and feedback loops will ensure iterative improvements, while evaluation metrics such as compliance rates, incident reduction, and worker satisfaction will validate the effectiveness. Ultimately, strong management commitment, policy support, and safety leadership are essential enablers for sustainable SPPE adoption in Sri Lankan HRBs.

6. Conclusion

This study addressed the critical problem of occupational hazards faced by high-rise building maintenance technicians (HRMTs) in Sri Lanka, particularly the inadequacy of general PPE in mitigating risks. Through a comprehensive literature review and validation through expert interviews the research identified key hazards, challenges in PPE usage, and strategies for improvement. The findings led to the development of a framework for implementing Smart Personal Protective Equipment (SPPE) specially to HRMTs in HRBs, offering a practical solution to overcome limitations of conventional PPE. The study also highlighted challenges in implementation of SPEE. Overall, this study contributes significantly to existing knowledge on SPPE and helps to uplift the health and safety of maintenance workers in high-rise buildings, who often perform high-risk tasks. For the development of this research, it is recommended to explore cost effectiveness, AI integration, long-term impacts on safety outcomes, and standardized certification procedures as future research. Conclusively, this work advances both academic understanding and industry practice by providing a structured pathway for SPPE adoption in HRB maintenance in Sri Lanka.

Figure 1, The Conceptual framework

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