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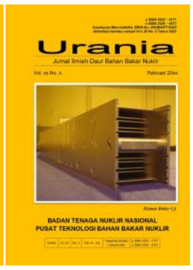

THE ROLE OF AGING – WORKFORCE MANAGEMENT IN MAINTAINING SAFETY PERFORMANCE IN HIGH – RISK NUCLEAR INSTALLATIONS

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ABSTRACT
THE ROLE OF AGING–WORKFORCE MANAGEMENT IN MAINTAINING SAFETY PERFORMANCE IN HIGH–RISK NUCLEAR INSTALLATIONS. The nuclear industry, as a high-reliability organization, faces serious challenges due to an aging workforce that could affect operational sustainability and safety performance. Although the literature on aging workforce management (AWM) is growing rapidly, empirical evidence linking AWM to safety performance in high-risk nuclear installations, particularly in developing countries, remains limited. This study aims to analyze the role of AWM in maintaining and improving safety behavior in nuclear installations in Indonesia. This study uses a quantitative, cross-sectional survey design with 281 employees from nuclear installations under the auspices of the National Research and Innovation Agency (BRIN). AWM is conceptualized as a multidimensional construct encompassing employee well-being and human resource practices, while safety behavior is measured through the dimensions of safety awareness and safety actions. Data were analyzed using Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM). The analysis results show that AWM has a positive and significant effect on safety behavior ($\beta = 0.607$; C.R. = 6.875; $p < 0.001$), with the measurement and structural models having a perfect fit. These findings confirm that well-being-oriented aging workforce management practices, continuous training, work ergonomics, and career planning can strengthen workers' safety awareness and compliance. Theoretically, this study extends the safety and human factors literature by positioning AWM as a strategic mechanism in maintaining the safety performance of high-risk socio-technical systems. In practice, the study's results provide policy implications for adaptive, sustainable human resource management to ensure the long-term safety of the nuclear industry in developing countries.

Keywords: Aging–workforce management, safety behavior, high–risk installations, nuclear safety.

INTRODUCTION

Although the international literature on aging workforce management has grown rapidly, empirical research linking workforce aging to safety performance in high-risk industrial contexts, particularly nuclear facilities in developing countries, remains very limited. Most studies focus on the physiological, cognitive, ergonomic, and productivity impacts of an aging workforce, particularly in the manufacturing, healthcare, and transportation sectors with relatively lower operational risks, and are predominantly concentrated in developed country contexts with well-established workforce regeneration systems and safety regulations [1],[2],[3],[4]. This situation limits the generalizability of the findings to complex socio-technical systems with very low risk tolerance, such as nuclear installations [5],[6].

The global nuclear industry faces serious workforce sustainability challenges that could threaten safety and operational continuity. As high-reliability organizations with a near-zero tolerance for failure, nuclear facilities rely heavily on the competence of their human resources, as even minor failures can have significant social, environmental, and economic consequences [7],[8],[9]. Two major demographic trends are of concern: the uncertainty surrounding the long-term development of the nuclear industry and the progressive aging of the professional and technical workforce, which simultaneously diminishes younger generations' interest and increases the risk of losing critical knowledge through the retirement of senior workers [6]. This aging workforce is part of a global demographic shift that has broad implications for workforce sustainability across various industrial sectors [9]. In high-risk industries such as the nuclear sector, this change is a strategic issue that brings together human resource management, operational safety, and long-term organizational resilience [7], [8].

In high-risk socio-technical systems, safety performance is determined not only by technology and procedures, but also by human factors, which play a significant role in both accident occurrence and prevention [7], [10]. IAEA reports indicate that the majority of the professional and technical workforce at nuclear installations is over 40 years old, with a significant proportion approaching retirement, while long-term recruitment patterns and low levels of new facility construction limit workforce regeneration [11]. On the one hand, senior workers are an organizational asset due to their experience, tacit knowledge, and strong understanding of safety culture [12]. On the other hand, aging carries physiological, cognitive, and ergonomic implications that can affect performance, emergency preparedness, and adaptation to new technologies. Without proper management, this condition can increase operational risks and reduce the effectiveness of nuclear safety systems [2].

Within the framework of modern nuclear safety and security, the human aspect holds a fundamental and irreplaceable position. The International Atomic Energy Agency (IAEA) consistently asserts that nuclear safety and security are highly dependent on personnel competence, organizational culture, leadership effectiveness, communication quality, and the ability to make appropriate decisions under both normal and abnormal operational conditions [13],[14]. From a human and organizational factors perspective, technical failures generally do not stem solely from mechanical or engineering weaknesses, but are often rooted in systemic weaknesses in management systems, deficiencies in safety culture, and inadequate human-technology interactions within complex socio-technical systems [15],[16]. In this context, the workforce plays more than just a role as technology operators; rather, it is a core component of a defense-in-depth strategy to prevent operational accidents and anticipate potential deliberate malicious acts [17],[18]. Therefore, the dynamics of workforce aging need to be understood as a strategic issue within the human factors domain, given its direct implications for the preservation of critical tacit knowledge, the intergenerational transmission of a safety culture, maintaining vigilance against security threats, and long-term organizational resilience [19],[20],[21]. Therefore, aging workforce management goes far beyond mere demographic or human resource management issues, but is an integral part of strengthening the human dimension of overall nuclear safety and security governance.

In the Indonesian context, this issue is becoming increasingly relevant. For more than six decades, Indonesia has operated three research reactors safely in reliably in Bandung, Yogyakarta, and Serpong. However, the zero-growth policy for civil servants and the moratorium on civil service recruitment from 2013–2017 have limited the regeneration of nuclear human resources at BATAN [22]. Consequently, the aging workforce composition impacts the organization's technical capacity, organizational culture, knowledge transfer mechanisms, and the sustainability of institutional competencies, leading to workforce shortages, the loss of critical skills and knowledge, and increased economic costs due to retirement [23],[24]. To date, empirical studies systematically analyzing these dynamics in the context of Indonesian nuclear installations are still very limited, even though managing an aging workforce is a key strategy for ensuring the sustainability and safety of the national nuclear industry in accordance with the applicable regulatory framework [25],[26].

Various studies have shown that the aging process affects workers' physical and functional capacities, including muscle strength, balance, flexibility, cardiorespiratory capacity, and vision and hearing, which can increase the risk of occupational accidents in high-risk environments such as nuclear installations [1],[4],[27],[28]. However, senior workers can also compensate for physical limitations through experience, tacit knowledge, and more mature cognitive strategies. Therefore, they can still contribute significantly to installation safety and security if supported by appropriate training and job design [29],[30]. From a theoretical perspective, senior workers constitute critical human capital in a safety management system, and the loss of this knowledge without an effective transition strategy can reduce an organization's capacity to manage risks and maintain long-term safety standards [31],[32],[33].

Addressing this research gap, this study integrates perspectives from safety science, human factors engineering, and strategic human resource management (SHRM) to analyze the role of aging workforce management in maintaining and improving safety performance and operational sustainability of nuclear installations. Indonesia was chosen as a relevant empirical study context because it has operated various nuclear research facilities for decades with relatively stable safety levels, but faces demographic challenges in including an increasing average age of the technical workforce and limited human resource regeneration [7], [8]. By using empirical data from Indonesian nuclear installations, this study also expands the literature, which developed country contexts have dominated.

This study aims to analyze the role of aging workforce management in maintaining the safety performance and operational sustainability of high-risk nuclear installations in Indonesia. The methodological approach used is a pure quantitative cross-sectional, through a quantitative survey at nuclear installations under the auspices of the National Research and Innovation Agency (BRIN), with confirmatory factor analysis and structural equation modeling (SEM) to examine the structural relationships between variables [1],[2],[3],[34],[35],[36]. The research findings are expected to make theoretical contributions to the development of the high-reliability organizations literature and to provide practical recommendations for adaptive, safe, and sustainable human resource management in high-risk industries [2],[37].

METHODOLOGY

a. Research Design and Participants

The This study used a quantitative, cross-sectional survey design to examine aging workforce management and safety behaviors in the context of high-risk installations. The unit of analysis was at the individual level, in line with safety literature that positions employee behavior as a primary output of organizational practices.

In this study, the aging workforce refers to individuals aged ≥45 years, according to the occupational health and human resource management literature [38],[39],[40],[41]. This age range was chosen because during this period significant changes occur in physical capacity, social roles, identity, and work experiences, which are relevant in aging workforce management practices and their impact on safety performance [42].

The study population consisted of employees working at nuclear installations in Serpong, Bandung, and Yogyakarta. A total of 281 respondents participated voluntarily, with an age distribution reflecting the aging workforce structure.

This study focused on examining relationships among variables across the entire respondent population, without comparing age groups. Despite involving younger employees, their perceptions of aging workforce management practices remain relevant because they impact organizational safety and cross-age interactions, thus contributing to understanding the effectiveness of AWM in maintaining overall safety behavior.

b. Data Collection Procedure

Primary data were collected via an online questionnaire distributed via internal communication channels using Google Forms. Participation was anonymous and voluntary. Prior to complete distribution, the instrument was piloted with a small group of employees to ensure item clarity and relevance, and minor revisions were made to enhance content validity. All items were measured using a five-point Likert scale, ranging from (1) strongly disagree to (5) strongly agree.

c. Variable Measurement

Aging Workforce Management (AWM) is conceptualized as a multidimensional construct reflecting organizational practices in maintaining the work capacity and safety performance of older workers. The instrument was adapted from a validated scale in the international literature and adapted to the Indonesian context. AWM is measured through five dimensions: aging workforce policies (GWP), training (PL), career development (PK), occupational ergonomics and health (EK), and pension plan management (PS) [24],[32],[43],[44].

Safety behavior is measured as a multidimensional construct reflecting an individual's active engagement and compliance with the organization's safety system. Referring to the framework of neal et al [45] and its development in the context of high-risk industries [47],[48], safety behavior is operationalized through four dimensions: safety compliance (KK), safety participation (RK), safety perception (SK), and safety knowledge (NK). Each dimension is measured using three items, allowing for a balanced evaluation of mandated and voluntary safety-related behaviors.

d. Data Analysis Techniques

Data were analyzed using Confirmatory Factor Analysis (CFA) to test construct validity and reliability, followed by Structural Equation Modeling (SEM) to examine the simultaneous relationships among variables. The SEM approach was chosen because it captures the complexity of latent relationships and minimizes measurement error. The analysis was conducted using SPSS and AMOS version 25.0.

RESULTS AND DISCUSSION

The initial stage of the analysis focused on processing descriptive statistics to identify general trends and patterns in respondent responses. This analysis provided an initial overview of respondents' perceptions of each dimension studied, which then served as the basis for further analysis. The results of the descriptive analysis for each dimension are presented in the following subsections.

a. Respondent Characteristics

Data collection through a questionnaire survey provided a comprehensive overview of the profile of respondents involved in operational and managerial activities at Indonesian nuclear installations. The demographic and professional characteristics of the respondents are summarized in Table 1.

Table 1. The Characteristics of Respondents

Age	Freq (n)	%
< 35 years	55	19.57
36 - 40 years	42	14.95
41 - 45 years	23	8.19
46 - 50 years	40	14.23
51 - 55 years	69	24.56
> 55 years	52	18.51

b. Feasibility of Factor Analysis

Before conducting the factor analysis, the data's feasibility was tested using Bartlett's Sphericity Test and the Kaiser–Meyer–Olkin (KMO) measure. The Bartlett's Sphericity Test was used to assess the existence of adequate correlation between variables, which is a primary prerequisite in factor analysis. A significance value less than 0.05 indicates that the correlation matrix does not form an identity matrix and, therefore, is suitable for further analysis.

Furthermore, the KMO measure was used to evaluate overall sample adequacy. A KMO value exceeding the threshold of 0.5 indicates that the data structure meets the eligibility criteria for factor analysis. The test results showed a Bartlett's Sphericity Test significance value of 0.000 (<0.05) and a KMO value of 0.846 for the AWM variable and 0.898 for the safety behavior variable. This confirms that the data have adequate correlation and sufficient sampling adequacy. Furthermore, all variables demonstrated Measure of Sampling Adequacy (MSA) values of 0.759–0.956 in this dataset. All values > 0.50 are suitable for factor analysis, with most indicators falling in the "good" to "excellent" range. Therefore, no indicators needed to be eliminated in the initial stages of factor analysis [36], [49].

Exploratory factor analysis (EFA) using Principal Component Analysis (PCA) with oblimin rotation showed that two indicators, NK2 and KK3, were eliminated because each had high cross-loadings and factor loadings below 0.50. After elimination, all remaining indicators had factor loadings between 0.558 and 0.981, indicating adequate to robust correlations with their respective factors and supporting convergent construct validity. The EFA results revealed a clear two-dimensional structure for each variable. In the AWM variable, the Employee Well-being dimension (KM2, PL2, PK2, PS1) showed high loading (0.836–0.981) and very good reliability (Cronbach’s alpha = 0.957), while the HR Practices dimension (KM1, PL1, PK1, EK1, EK2, PS2) had moderate to high loading (0.606–0.756) with good reliability (Cronbach’s alpha = 0.773). In the safety behavior variable, the Safety Awareness dimension (SK1, SK2, SK3, NK1, NK3) showed a loading of 0.707–0.975 and high reliability (Cronbach’s alpha = 0.868), while the Safety Actions dimension (RK1, RK2, RK3, KK1, KK2) had a loading of 0.558–0.922 with very good reliability (Cronbach’s alpha = 0.916).

To test for potential common-method bias, Harman's single-factor test was conducted via factor analysis without rotation [50]. The results showed that the largest single factor accounted for 44.122% of the total variance, which is still below the 50% threshold, so that common method bias does not dominate the data structure [51].

Overall, these results confirm a stable factor structure and strong internal consistency, making the instrument suitable for further analysis [52].

c. Data Normality Test Result

Before conducting Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM), the data normality assumption was first tested. Normality testing is necessary to determine the appropriate estimator in SEM analysis using AMOS. Normality testing in this study was conducted by analyzing the skewness and kurtosis of each research variable.

Based on the results of the descriptive statistical analysis, it was identified that all research indicators had skewness values ranging from -1.024 to -0.083. These values are within the normality criteria recommended by Hair et al (2018), which range from -2 to +2. Similarly, kurtosis values ranged from -1.256 to 1.287, meeting the normality criteria with limits of -7 to +7.

Several indicators showed distributions approaching normality, such as RK1 (skewness = -0.083, kurtosis = -0.327) and SK3 (skewness = -0.205, kurtosis = -1.151). Although several indicators had slightly higher skewness values, they remained within normal limits, including KM2 (-0.968), PL2 (-1.001), and PK2 (-1.024). The consistent negative skewness pattern across all indicators indicates that respondents tended to rate all measured aspects highly.

With the univariate normality assumption met for all indicators, this study could use the Maximum Likelihood (ML) estimator in CFA and SEM analyses. The ML estimator is the most commonly used method and possesses consistency, efficiency, and asymptotic normality when the normality assumption is met [36].

Thus, the research data meet the assumption of univariate normality and are ready for further analysis using Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM) techniques with the Maximum Likelihood estimator. These results provide a strong basis for conducting a confirmatory analysis of the measurement model and testing the research hypotheses.

d. CFA Test Results

The Reliability and construct validity were evaluated using Composite Reliability (CR) and Average Variance Extracted (AVE), calculated using standard formulas. CR values above 0.70 and AVE values above 0.50 indicate that the construct has adequate internal consistency and meets convergent validity criteria.

The Confirmatory Factor Analysis (CFA) results in Table 2 indicate that both constructs in this study meet the criteria. Within the Safety Behavior construct, two dimensions were identified: Safety Awareness (SK1, SK3, NK1) and Safety Action (RK1, RK2, KK1). These two dimensions demonstrated good reliability with CR values of 0.817 and 0.800, respectively, and AVE values above 0.60, confirming convergent validity.

Similarly, for the AWM construct, CFA results revealed two dimensions: Employee Well-Being (PS2, EK1, PK1) and Human Resource Practices (PK2, PL2, KM2). The CR values for each dimension were 0.774 and 0.830, respectively, with an AVE value above 0.55, indicating that these indicators consistently and adequately represent the latent construct being measured.

Overall, these results indicate that the measurement model has good reliability and convergent validity, making it suitable for further analysis using Structural Equation Modeling (SEM) as shown in Figure 1 [36].

Table 2. CFA Results for Safety Behavior and Aging Workforce Management

Variable	Dimension	Indicator	Standardized Loading	CR	AVE
Safety Behavior	Safety Awareness	SK3	0.871	0.817	0.625
		SK1	0.798		
		NK1	0.593		
	Safety Actions	RK2	0.880	0.800	0.614
		RK1	0.959		
		KK1	0.739		
Aging Workforce Management	Employee Well-being	PS2	0.733	0.774	0.554
		EK1	0.643		
		PK1	0.514		
	HR Practices	PK2	1.002	0.830	0.650
		PL2	0.993		
		KM2	0.776		

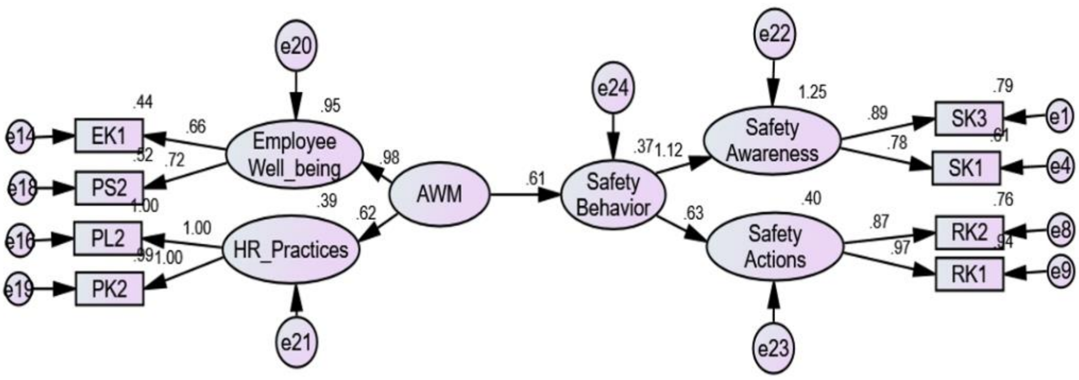

Figure 1. SEM Model of Safety Behavior and Aging Workforce Management

e. Structural Equation Model Analysis

Based on the CFA model's goodness-of-fit test results (Table 3), the measurement model demonstrates an excellent fit with the empirical data. The CMIN/DF value of 1.324, which is below the recommended limit (<3), indicates that the model has a good level of parsimony. Furthermore, the p-value (CMIN) of 0.177 (>0.05) indicates that the difference between the estimated and empirical covariance matrices is not significant, so the model is statistically acceptable [36].

The incremental fit indices also showed very satisfactory results. The NFI (0.993), RFI (0.986), IFI (0.998), TLI/NNFI (0.997), and CFI (0.998) were all well above the 0.90 threshold, confirming that the model represents the relationships among the latent constructs very well. Furthermore, the absolute fit indices showed consistent results. The RMSEA value of 0.031, which is below the maximum limit of 0.08, indicates a low level of approximation error. This is supported by the PCLOSE value of 0.807 (>0.05), indicating a close fit between the model and the data [52].

Table 3. CFA Model Goodness of Fit Index

Index	Value	Criteria	Conclusion
CMIN / DF	1,324	< 3	Good
p-value (CMIN)	0,177	> 0,05	Acceptable
NFI	0,993	> 0,90	Very good
RFI	0,986	> 0,90	Very good
IFI	0,998	> 0,90	Very good
TLI / NNFI	0,997	> 0,90	Very good
CFI	0,998	> 0,90	Good
RMSEA	0,031	< 0,08	Good
PCLOSE	0,807	> 0,05	Parsimonious model
AIC	77,864	–	Good model stability
ECVI	0,228	–	Adequate sample
Hoelter (0,05)	430	> 200	Good

In terms of parsimony and model stability, the AIC value of 77.864 and the ECVI of 0.228 indicate that the model is efficient and has good potential for stability when applied to other samples. Furthermore, the Hoelter Critical N value (0.05) of 430, which far exceeds the minimum limit of 200, confirms that the sample size used is sufficient to support model estimation.

Overall, all goodness-of-fit indices indicate that the CFA model has excellent fit, is stable, and parsimonious, making it suitable for further analysis, including structural equation modeling.

f. Results of Structural Model Hypothesis Testing

Hypothesis testing was conducted using Structural Equation Modeling (SEM) with reference to regression weights, critical ratios (CR), and significance levels. The estimation results indicate that the tested structural relationships have a direction and strength of influence consistent with the research hypothesis, as shown in Table 4.

The analysis shows that Aging Workforce Management (AWM) has a positive and significant association with Safety Behavior (BS). The AWM → BS path has a critical ratio of 6.875, exceeding the minimum threshold of 1.96, with a p-value of < 0.001. The standardized regression weight value of 0.607 shows that AWM is significantly related to BS. This finding indicates that improvements in administrative management and the work environment directly contribute to enhanced employee safety. In addition to the relationships between constructs, the estimation results also show that all indicators significantly influence their respective constructs. The indicators in the AWM construct, represented by the Employee Well-being and HR Practices dimensions, and the indicators in the Safety Behavior construct, represented by Safety Awareness and Safety Actions, have C.R. values above 1.96, with p < 0.001. The standardized indicator loadings ranged from 0.665 to 0.995, indicating a substantial contribution of the indicators in reflecting the latent construct.

Analysis by age group showed that the relationship between Aging Workforce Management (AWM) and safety behavior was significant in both groups of respondents, but with varying strengths. The effect of AWM on safety behavior was stronger in workers aged over 45 years ($\beta = 0.700$; $p < 0.001$) compared to workers aged under 45 years ($\beta = 0.482$; $p < 0.001$). This finding suggests that aging workforce management practices tend to have a greater impact on senior workers, who generally have longer work experience and broader tacit knowledge of safety procedures. In the context of high-risk organizations such as nuclear installations, the experience and knowledge transfer of senior workers are important factors in maintaining an organization's safety culture.

Table 4. Results of Structural Model Hypothesis Testing

Hypothesis	Relationship	Estimate	Standardized	C.R.	P	Conclusion
H1	AWM → BS	0,860	0,607	6,875	<0,001	Accepted

Overall, these results confirm that the proposed structural model exhibits significant and empirically consistent associations. Thus, hypothesis H1, which states that aging workforce management is positively associated with Safety Behavior is accepted. This finding supports the argument that good management practices and a good work environment are important factors in improving employee safety.

DISCUSSION

The results of this study indicate that Aging Workforce Management is positively and significantly associated with safety behavior (BS) in Indonesian nuclear installations, with a standardized estimate of 0.607 and a CR of 6.875 ($p < 0.001$). This finding confirms that administrative management practices, the work environment, training, career development, and attention to the well-being of older workers directly increase employee safety awareness and compliance [24],[32],[43],[44]. The AWM and BS indicators also contributed significantly to their respective constructs, supporting the model's convergent validity and internal reliability [52].

In the context of this research, nuclear installations fall under the National Research and Innovation Agency, where AWM implementation has not yet been fully structured as a formal policy. However, most respondents were previously employees of the National Nuclear Energy Agency, which has partially implemented practices for managing aging workers, including ongoing training, supportive work environments, and retirement preparation. Therefore, the AWM construct in this study reflects existing organizational practices, although not yet systematically integrated.

Although this study involved respondents from established institutions, the findings remain relevant for application to new institutions. This is because the Aging Workforce Management (AWM) construct in this study not only represents the existence of a formal policy program but also reflects a range of human resource management practices for managing an aging workforce, such as ongoing training, a supportive work environment, competency development, and retirement preparation. These practices are adaptive and can be implemented in other organizations with similar operational characteristics. In the context of nuclear installations as high-reliability organizations, managing senior workers is crucial for maintaining the sustainability of technical competencies, transferring tacit knowledge, and complying with safety procedures [1],[4],[27],[28].

For institutions that do not yet have a structured AWM program, the findings of this study also provide a framework for its gradual implementation. The AWM indicators validated in this study can therefore be used as an initial reference in developing human resource policies. Organizations can begin with partial interventions, such as adaptive training, work ergonomics support, and senior worker knowledge transfer programs, then integrate these into existing safety management systems. Thus, this study not only evaluates existing practices, but also provides an empirical basis for new institutions to develop aging workforce management to support improved safety behaviors in high-risk organizations [46],[47],[48].

Theoretically, these findings reinforce the safety science and human factors engineering literature, which emphasizes the importance of senior human resource capacity in high-risk organizations [1],[4],[27],[28]. Senior workers not only bring critical experience and tacit knowledge, but appropriate AWM practices also enable them to compensate for physiological or cognitive limitations, thereby continuing to contribute to high safety performance [12] Thus, this study highlights the integration of strategic human resource management with safety systems as a key factor in maintaining high-reliability organizations in high-risk industrial contexts [2],[37].

Practically, these findings emphasize the need for organizational policies that adapt to workforce demographics, including retirement planning, ongoing training, and ergonomic job design [31],[32]. This approach not only improves operational safety but also ensures the sustainability of technical competencies and critical knowledge at nuclear facilities facing workforce regeneration challenges [8],[7] This study also provides an empirical basis for developing AWM programs that can be adopted in other high-risk industries in developing countries, thereby expanding the literature, which has been dominated by developed-country contexts [46],[47],[48].

Finally, although the results indicate a significant causal relationship, the limitations of the cross-sectional design and the use of self-perception data indicate the need for longitudinal research and a combination of objective indicators to understand the long-term dynamics of AWM's influence on safety behavior [54],[52].

CONCLUSIONS

This study provides empirical evidence that aging workforce management (AWM) plays a significant role in improving safety behavior at high-risk nuclear installations in Indonesia. The analysis shows that management practices focused on employee well-being, competency development, ongoing training, ergonomics and occupational health, and retirement planning effectively strengthen worker safety awareness and actions. These findings confirm that an aging workforce is not merely a source of risk but rather critical human capital whose contribution to safety can be optimized through appropriate management strategies. Theoretically, this study extends the literature on high-reliability organizations by positioning AWM as a key mechanism in maintaining the safety performance of high-risk socio-technical systems. Practically, the results emphasize the importance of integrating aging workforce management into safety management systems to ensure the long-term operational sustainability and safety of the nuclear industry.

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RESEARCH LIMITATIONS

This study has several limitations. First, the cross-sectional survey design limits the ability to draw causal longitudinal conclusions. Second, although the aging workforce has been explicitly defined, this study did not conduct a comparative analysis across age groups; the differences in safety behavior dynamics between older and younger workers have not been specifically explored. Therefore, future research is recommended to conduct cross-generational analyses or a longitudinal approach to gain a more comprehensive understanding of the role of aging workforce management in the context of high-risk installations..

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