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Impact of Managerial Safety Failure on Physical-Technical Risk in Corporate Laboratories

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Abstract

Purpose: With the acceleration of the Fourth Industrial Revolution and the expansion of the Serious Accidents Punishment Act (SAPA) in 2024, the establishment of effective safety management systems in corporate research institutes has become critical. This study aims to quantitatively determine the impact of Managerial Safety Failure on Physical-Technical Risks (chemical, mechanical, electrical, etc.) using detailed safety inspection data. **Research design, data and methodology:** The study utilized raw data from detailed safety inspections collected directly from 100 corporate research institutes (N=100) in the metropolitan area in 2025. The core variable, risk level, was quantified using the Risk Weight Index (RWI) derived from the Korea Risk Assessment System (KRAS), applying differential weights based on hazard severity. **Results:** First, managerial safety failure showed a statistically significant positive correlation with all physical-technical risk factors ($p<.001$), peaking in Chemical Safety ($r=.897$). Second, hierarchical regression confirmed that managerial failure is a decisive predictor, explaining 80.7% of the variance in chemical safety risk. **Conclusions:** This study proves that the absence of a managerial safety system is a key leading indicator amplifying potential risks into actual accidents. Consequently, corporate safety management must shift from a 'paperwork-centered' approach to an 'on-site operational effectiveness-centered' paradigm prioritizing real-time hazard prevention.

Keywords : Corporate Research Institute, Detailed Safety Inspection, Managerial Safety Failure, Risk Weight Index (RWI), Serious Accidents Punishment Act (SAPA)

JEL Classification Code: J28, K32, O32

1. Introduction

1.1. Background and Necessity of Research

In modern society, corporate research institutes serve as the source of national technological competitiveness and a key base for creating future growth engines. However, due to the nature of R&D activities, these institutes are high-risk environments that handle small quantities of various hazardous chemicals, use high-pressure gas and precision mechanical equipment in combination, and face unpredictable variables during experiments. Despite these potential risks, past laboratory safety management has been relatively neglected compared to manufacturing or construction sites, and issues regarding the concealment or downplaying of accidents due to concerns about shrinking research activities have been consistently raised. In fact, according to statistics from the Ministry of Science and ICT (2025), the laboratory accident rate in domestic corporate research institutes rose from 0.8% in 2019 to 1.2% in 2025, marking an approximate 1.5-fold increase over the past five years. This distinct upward trend suggests that safety management in the research field is facing its limits

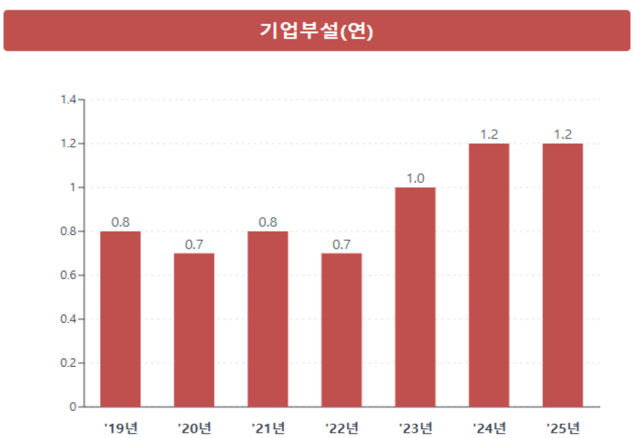

Figure 1. Annual Accident Rate in Corporate Research Institutes (2019-2024) Source: Ministry of Science and ICT (2025).

However, the enforcement of the "Serious Accidents Punishment Act" (hereinafter referred to as SAPA) in 2022 and its full expansion to workplaces with five or more employees in 2024 are fundamentally changing the paradigm of laboratory safety management. Management executives are now obligated not only to comply with legal standards but also to establish and implement a substantially functioning "Safety and Health Management System." Kim et al. (2025) emphasized in recent research that SAPA requires not simple compliance with regulations but the establishment of an autonomous prevention system where companies identify and improve hazards and risk factors themselves. However, there is still a tendency in the field to focus on formal paperwork to avoid legal punishment. According to a survey by Cho et al. (2022), although companies' safety budgets and organizations have expanded since the law's implementation, it remains to be verified whether these quantitative investments lead to an actual reduction in accidents. In fact, recent statistics from the Ministry of Employment and Labor (2024) indicate that a significant number of laboratory accidents stem from managerial factors, such as non-compliance with basic safety rules. Existing prior studies on laboratory safety have been mainly limited to safety consciousness surveys of research personnel or analysis of specific accident cases. These approaches have limitations in quantitatively grasping the objective risk level of research institutes, and in particular, there was a lack of empirical verification of the causal relationship between "managerial factors" and actual "physical risks." It is time for a "System Approach," which views safety accidents not as random occurrences but as events that happen when organizational managerial defects accumulate and encounter unsafe conditions in the field.

In particular, unlike manufacturing sites that repeat standardized processes, laboratories face high uncertainty of potential risks due to the frequent synthesis of new substances and changes in experimental conditions. In this environment, physical and hardware investments, such as replacing aging equipment or providing protective gear, have clear limitations in preventing accidents. Nevertheless, current corporate safety management is often biased towards visible facility improvements, while quantitative evaluation of "software capabilities," such as the operation of management systems or compliance with procedures—which are the root causes of actual accidents—remains relatively insufficient. This "blind spot in management" leads to a "Safety Paradox" where accidents recur despite the introduction of expensive safety equipment. Therefore, empirically identifying how much the absence of managerial factors amplifies actual physical risk is an urgent prerequisite for resetting the direction of corporate safety investment from "facility-centered" to "management system-centered."

1.2. Purpose of Research

This study aims to quantitatively demonstrate the impact of "Managerial Safety Failure" in corporate research institutes on "Physical-Technical Risks" such as chemical, mechanical, and electrical risks, utilizing the latest detailed safety inspection data from 2025. The results of detailed safety inspections enhance the reliability of the study as they are objective data derived from on-site inspections by experts, unlike survey-based data. The specific objectives of the study are as follows: First, analyze the correlation between the managerial safety level of 100 corporate research institutes and the risk levels by field (Chemical, Mechanical, Electrical, Fire, Gas, Industrial Hygiene). Second, verify through regression analysis the extent to which managerial safety failure predicts each physical risk while controlling for exogenous variables such as the number of research personnel. Third, apply the Risk Weight Index (RWI) reflecting the severity of each finding to add sophistication to the analysis and present differentiated safety management strategies tailored to corporate characteristics.

2. Literature Review

2.1. Changes in Safety and Health Management Systems and Importance of Managerial Factors

Recently, the paradigm of laboratory safety management has been rapidly shifting from simple physical protective measures to a system-centered autonomous prevention system. The core of SAPA lies in "prevention" rather than post-accident "punishment," and explicitly mandates the "establishment and implementation of a safety and health management system" as a means to achieve this. Lee et al. (2022) pointed out that small-scale workplaces face significant difficulties in fulfilling legal obligations due to a lack of manpower and resources, emphasizing that response strategies through the efficiency of "managerial systems" rather than hardware investments are essential to overcome this. In particular, the "Act on the Establishment of Safe Laboratory Environment," amended and enforced in May 2024, further highlights the importance of these managerial factors. The amended laws specify the qualification requirements for laboratory safety environment administrators to strengthen "professionalism" and mandate substantial risk assessments and preliminary hazard analysis rather than formal inspections (National Law Information Center, 2024). This legally identifies that laboratory safety should not be a simple administrative task but must be operated by a professional "Managerial System." Therefore, "Managerial Safety Failure" defined in this study refers to total defects that hinder the operability of the system, such as omission of daily inspections, non-compliance with safety rules, and formalization of risk assessments, going beyond simple document deficiencies.

2.2. Characteristics of Laboratory Accidents and System Approach

Laboratories differ from manufacturing sites in that they frequently perform non-routine tasks, such as synthesizing new substances or changing process conditions, resulting in high uncertainty of potential risks. Lim and Kim (2024) statistically identified through multiple correspondence analysis of accident cases that laboratory accidents are caused by a complex combination of non-routine characteristics, such as handling unverified methods or substances, and researchers' unsafe acts.

Traditionally, Heinrich's Law has been the dominant theory in safety management, positing that 88% of accidents are caused by unsafe acts of people. However, this perspective has limitations in that it attributes the responsibility for accidents primarily to individual workers, obscuring the structural problems of the organization. In contrast, the System Approach adopted in this study views individual errors as merely symptoms, with the underlying causes lying in organizational processes and culture. This study supports the modern safety engineering perspective that removing latent defects in the management system is more effective for fundamental accident prevention than blaming individuals for slip-ups or lapses.

Reason (1997)'s "Swiss Cheese Model," a modern safety theory, interprets these accidents as defects in the organizational system. According to this model, accidents occur when managerial failures, which are "Latent Conditions" of the organization, pass through holes in the defense barriers and combine with "Active Failures" in the field. In particular, researchers, who are high-level expert groups, tend to skip safety procedures due to optimistic bias overestimating their knowledge. In the absence of strong managerial control, these human errors become uncontrollable. In other words, managerial defects do not cause accidents by themselves, but act as a "Root Cause" that induces or neglects physical and technical risks such as neglect of chemicals, poor grounding of electrical equipment, and deactivation of mechanical safety guards. Therefore, controlling managerial factors becomes the most certain "Leading Indicator" for preventing physical accidents.

2.3. Managerial Sensitivity according to Risk Attributes

Not all risks respond equally to managerial factors. The more complex and fluid the system, the greater the importance of managerial control. In particular, the field of Chemical Safety requires real-time management due to the state changes and reactivity of substances. Labeling of reagents, separation and storage of waste liquids, and operation of fume hoods require continuous "Procedure Compliance" by researchers, which relies entirely on the control power of the management system. On the other hand, Electrical Safety or Gas Safety has strong hardware characteristics of the equipment, so the initial installation status or degree of aging has a relatively large impact on the risk level. In other words, chemical safety responds more sensitively to human behavior and management procedures, while equipment safety is more sensitive to mechanical defects. Accordingly, this study establishes the hypothesis that the influence of managerial failure will appear in the order of Chemical > Mechanical > Electrical and intends to verify this through detailed safety inspection data.

3. Research Methods and Materials

3.1. Research Model and Hypotheses

This study set "Managerial Safety Failure" of corporate research institutes as the independent variable and "Physical-Technical Risk" by field as the dependent variable. In addition, "Number of Researchers" was set as a control variable to exclude the effect of research institute size, constructing a hierarchical regression model.

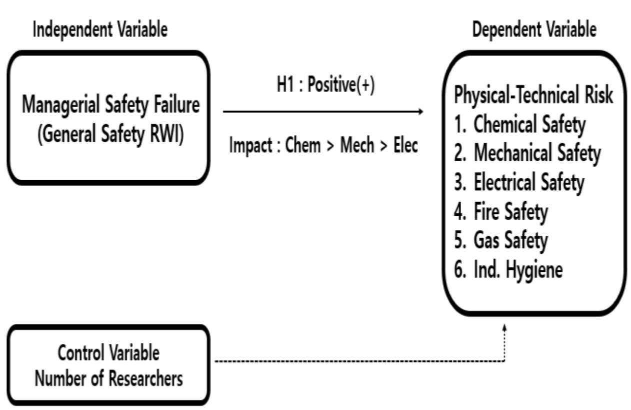

Figure 2: Research Model

Hypothesis 1: Managerial Safety Failure (General Safety RWI) will have a positive (+) correlation with all Physical-Technical Risks (Chemical, Mechanical, Electrical, Fire, Gas, Industrial Hygiene).
Hypothesis 2: Even after controlling for the number of research personnel, Managerial Safety Failure will significantly predict Physical-Technical Risks, and its influence will be greatest in the field of Chemical Safety.

3.2. Data Collection and Subjects

The subjects of analysis in this study are 100 corporate research institutes (N=100) located in the metropolitan and Chungcheong areas from January to November 2025. To ensure data reliability, raw data from detailed safety inspection reports conducted directly by the researcher or by accredited safety diagnosis agencies were collected. The sample consists of various industries such as electronics, materials/chemicals, machinery, and life sciences, enhancing the generalizability of the research results.

3.3. Measurement of Variables and Calculation Basis (Risk Weight Index)

The Risk Weight Index (RWI), the core variable of this study, was calculated by assigning weights according to the severity grade of risk factors found in each laboratory, rather than simply summing the number of findings. This is to quantify the actual risk level by not treating minor violations and fatal accident risks equally.
Independent Variable: Managerial Safety Failure Measured by converting findings in the "General Safety" field among detailed safety inspection items into RWI. This represents defects in the management system such as lack of safety and health management regulations, failure to complete safety education, and failure to conduct daily inspections.
Dependent Variable: Physical-Technical Risk Calculated as RWI scores for hazardous and risk factors found in six technical fields: Chemical, Mechanical, Electrical, Fire, Gas, and Industrial Hygiene.
RWI Calculation Formula: In this study, risk grades derived from KRAS diagnosis results were classified into four levels with differential weights: Low Risk (2.5 points), Medium Risk (5.0 points), High Risk (7.5 points), and Very High Risk (10.0 points). The final RWI is calculated using the following equation:

$$RWI = (N_{Low} \times 2.5) + (N_{Medium} \times 5.0) + (N_{High} \times 7.5) + (N_{VeryHigh} \times 10.0)$$

3.4. Analysis Methods

The collected data were analyzed using SPSS 26.0 for Windows. First, descriptive statistics analysis was performed to check the mean and standard deviation of variables. Second, Pearson's product-moment correlation analysis was conducted to identify the relationship between major variables. Third, Hierarchical Multiple Regression analysis was conducted to verify the pure in fluence of managerial factors. In this process, the independence of residuals (Durbin-Watson), multicollinearity (VIF), and normality (Shapiro-Wilk) tests were performed to strictly confirm whether statistical assumptions were met.

4. Results and Discussion

4.1. Descriptive Statistics and Data Characteristics

The descriptive statistics for the major variables of the 100 corporate research institutes analyzed are shown in Table 1. The mean of the independent variable, Managerial Safety Failure (General Safety RWI), was 10.10 (SD=4.42). This implies that the surveyed research institutes contain an average of about 10 points of managerial defects. Looking at the dependent variable, Physical-Technical Risk, Chemical Safety RWI was the highest with an average of 24.35 (SD=12.65). This suggests that risks related to chemical handling occur most frequently and seriously in corporate laboratories. Next, Mechanical Safety (M=19.46), Electrical Safety (M=15.58), and Fire Safety (M=12.47) showed high risks in that order. In particular, the Industrial Hygiene (M=8.21) field was evaluated as having relatively low risk, which is interpreted as being due to the nature of detailed safety inspections focusing on visible physical equipment.

Table 1: Descriptive Statistics of Key Variables (N=100)

Variable	Min	Max	Mean(M)	SD
Managerial Safety Failure(indep.)	0.00	20.50	10.10	4.42
Chemical Safety Risk(Dep.)	0.00	56.10	24.35	12.65
Mechanical Safety Risk	0.00	43.00	19.46	10.50
Electrical Safety Risk	0.00	37.60	15.58	8.07
Fire Safety Risk	0.00	30.90	12.47	6.38
Gas Safety Risk	0.00	21.70	10.79	4.86
Industrial Hygiene Risk	0.00	19.10	8.21	4.39

4.2. Correlation Analysis

The results of Pearson correlation analysis between major variables are presented in Table 2. As shown in Table 2, there are strong positive correlations (p<.001) between managerial failure and physical risks, peaking at r=.897 for chemical safety, which supports the risk hierarchy hypothesis. This implies that as the managerial system becomes poorer, the risk of chemical safety accidents increases almost linearly. Very strong correlations were also confirmed in Mechanical Safety (r=.824) and Electrical Safety (r=.742). Fire Safety (r=.535), Gas Safety (r=.463), and Industrial Hygiene (r=.412) also showed significant relationships, but the correlation was somewhat lower compared to chemical or mechanical fields.

Table 2: Correlations between Managerial Safety Failure and Physical-Technical Risks

Variable	1	2	3	4	5	6	7
1. Managerial Failure	1						
2. Chemical Safety Risk	.897***	1					
3. Mechanical Safety Risk	.824***	.739***	1				
4. Electrical Safety Risk	.742***	.677***	.619***	1			
5. Fire Safety Risk	.535***	.498***	.482***	.471***	1		
6. Gas Safety Risk	.463***	.454***	.364***	.284***	.158***	1	
7. Industrial Hygiene	.412***	.366***	.303***	.361***	.092***	.222***	1

*Note: N=100 / *p<.05 / **p<.01 / ***p<.001*

4.3. Hierarchical Multiple Regression Analysis

To verify the unique influence of Managerial Safety Failure on physical risk, hierarchical regression analysis was conducted with "Chemical Safety Risk," which showed the highest correlation, as the dependent variable (Table 3).

Table 3: Hierarchical Regression on Chemical Safety Risk

Step	Variable	Unstandardized Coeff. (B)	S.E.	Standardized Coeff. (β)	t	p	VIF
Model 1	(Constant)	25.216	2.611	-	9.659	.000	
	Researchers	-0.015	0.040	-0.038	-0.379	.706	1.000
Model 2	(Constant)	-0.759	1.734	-	0.438	.662	-
	Researchers	-0.015	0.017	-0.029	-0.839	.403	1.000
	Managerial Failure	2.571	0.128	0.897	20.09	.000	1.000
	R^2 ($Adj\ R^2$	.807(.803)					
	F-change	202.203***					
	Durbin-Watson	2.117					

*Note: Dependent Variable = Chemical Safety Risk (RWI) / *p<.05 / **p<.01 / ***p<.001*

Verification of Model Fit: First, as a result of verifying statistical assumptions, the Durbin-Watson statistic was 2.117, close to the reference value of 2, confirming no autocorrelation of residuals. In addition, the Variance Inflation Factor (VIF) was calculated as 1.000. This implies that the control variable "Number of Researchers (Physical Size)" and the independent variable "Managerial Safety Failure (Managerial Behavior)" are statistically independent dimensions. In other words, managerial failure can occur independently regardless of the size of the research institute, and thanks to this orthogonality between variables, we were able to robustly estimate the pure influence of the independent variable without concerns about multicollinearity. Finally, the Shapiro-Wilk normality test on residuals (Statistic=0.991, p=0.768) showed a significance probability greater than 0.05, adopting the null hypothesis that residuals follow a normal distribution, thereby securing the reliability of the regression analysis.

Analysis Results: In Step 1 analysis, the control variable "Number of Researchers" was input, but the regression model was not statistically significant (F=0.143, p=.706) and did not explain Chemical Safety Risk at all (R^2= .000). This suggests that a large scale or number of personnel in a research institute does not automatically guarantee safety. In Step 2, adding the independent variable "Managerial Safety Failure" drastically increased the explanatory power of the model (R^2) to 80.7% (F=202.2, p<.001). Looking at the regression coefficient (β), Managerial Safety Failure showed a very strong positive (+) influence of β=.897 (t=20.09, p<.001) on Chemical Safety Risk. This implies that when other conditions are equal, a 1-unit increase in managerial defects leads to an increase of about 0.9 units in chemical safety risk, statistically proving that managerial factors are the most critical variable determining chemical accident risk.

4.4. Discussion

This study empirically analyzed the impact of Managerial Safety Failure in corporate research institutes on Physical-Technical Risk based on Detailed Safety Inspection data (RWI). The academic and practical discussions on the derived major results are as follows.

First, statistical analysis showed that Managerial Safety Failure had a strong positive (+) correlation with all technical risk factors such as chemical, mechanical, and electrical, and regression analysis also confirmed it as a decisive variable explaining about 81% of Chemical Safety Risk. This is interpreted as an empirical verification of the accident mechanism suggested by Reason (1997)'s "Swiss Cheese Model" in the environment of Korean corporate research institutes. In other words, "Latent Failures" at the organizational level, such as lack of documentation, failure to complete training, and omission of inspections, act as holes in the defense barriers, suggesting that they become "Leading Indicators" that eventually induce actual risks such as chemical leaks or mechanical malfunctions in the field.

Second, the influence of managerial factors showed differential sensitivity in the order of "Chemical (β=.897) > Mechanical (β=.824) > Electrical (β=.742)" depending on the attributes of the risk. Chemical safety has characteristics that rely absolutely on researchers' actions and procedure compliance, such as reagent storage, waste disposal, and fume hood operation. Therefore, if systemic control becomes loose, the possibility of transition to immediate risk is highest. On the other hand, electrical safety is judged to have a somewhat lower correlation with managerial factors because hardware factors of the facility itself, such as grounding or earth leakage circuit breakers, play a relatively large role. This suggests that laboratory safety management requires a "Targeted Strategy" tailored to the characteristics of each technical field, rather than a uniform approach.

Based on the analysis results of this study, specific management strategies tailored to the characteristics of each technical field are proposed. For Chemical Safety, where the correlation with managerial failure is highest, strict control systems such as pre-approval systems for high-risk substances and mandatory double-checking of waste disposal procedures should be prioritized. In Mechanical Safety, regular maintenance schedules and lockout/tagout (LOTO) procedures must be institutionalized to prevent risks caused by equipment aging or malfunction. Although Electrical Safety showed a relatively lower correlation, it still requires managerial attention to ensure that safety devices like earth leakage circuit breakers are not arbitrarily deactivated by researchers for convenience. This differentiated approach will enable companies to allocate limited safety budgets and resources more efficiently.

Third, the number of research personnel input as a control variable did not show a significant influence. This means that a large scale of a research institute does not necessarily mean it is safe, and conversely, even a small research institute can secure sufficient safety if a systematic management system operates. In conclusion, this study clarified that what determines the safety level of a laboratory is not the quantity of "Resources" input but the qualitative substantiality of "Management."

4.5. Limitations

Although this study empirically verified the safety management mechanism of corporate research institutes, it has the following limitations, and based on this, suggestions for future research are made. First, since this study utilized Cross-sectional data at a specific point in time, there is a limitation in clearly verifying the time-series causal relationship of whether physical risks actually decrease after managerial system improvement. Future research needs to construct Panel Data to track and observe changes in risk levels before and after managerial intervention. Second, the subject of analysis was limited to 100 research institutes in the metropolitan and Chungcheong areas, so a cautious approach is needed to generalize this to the characteristics of all research institutes in Korea. In the future, external validity of the research should be enhanced through stratified sampling on a nationwide scale. Third, since only quantitative indicators (RWI) were used, qualitative factors such as researchers' safety consciousness or organizational culture could not be directly reflected. Future research requires the application of Mixed Methods combining surveys and interviews.

4. Results and Discussion

This study quantitatively determined the impact of the managerial safety system of corporate research institutes on actual physical risk amidst the changing policy environment of the 2025 amendment to the Laboratory Safety Act and the strengthening of SAPA. Research results proved that Managerial Safety Failure is a "Root Cause" that amplifies potential technical risks in the laboratory, and its influence was most significant in the chemical field, which has high reliance on researcher behavior. These results suggest that corporate safety management strategies should shift from focusing on expensive equipment investment to improving "Managerial Safety Indicators." Activities that lower managerial RWI scores, such as substantializing safety education, making daily inspections a habit, and complying with safety rules, are the most efficient solutions to prevent serious accidents. In terms of policy, the government's safety inspection paradigm must shift from detecting equipment defects to evaluating the operability of the safety and health management system, and precise supervision centered on systems should be strengthened, especially for research institutes with a high proportion of chemical fields such as bio and materials.

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