

Article

Accident Characteristics and Cost-Based Risk Control Options by Nationality in Korean Aquaculture

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Abstract

The Korean aquaculture sector relies heavily on foreign workers, who face elevated risks due to language barriers and limited safety training. This disparity necessitates data-driven safety interventions addressing specific worker vulnerabilities to ensure sustainable industry growth. This study quantitatively investigated accident characteristics and economic losses by nationality in Korean aquaculture by integrating 325 approved cases (2018–2022) from Industrial Accident Compensation Insurance (268 Korean; 57 foreign) and field survey data into the Formal Safety Assessment and Fault Tree Analysis frameworks recommended by the International Maritime Organization (IMO). The study revealed that entanglement during machinery operations accounted for 63.5% of the total cost among foreign workers. For Korean workers, slip and fall accidents were most frequent, while falls from height were the most severe in terms of unit cost and fatality. Based on the importance index and Human Element analysis, four risk control options were proposed: guarding and interlocks retrofit, multilingual training for foreign workers, and fall-protection upgrades and permit-to-work systems with lockout/tagout for Korean workers. Scenario analysis demonstrated consistent cost-saving effects. Both direct and indirect costs were incorporated into total loss estimation, with indirect costs calculated as 0.5–1.0 times the direct costs following the Ministry of Employment and Labor (2021).

Keywords: aquaculture safety; foreign workers; Formal Safety Assessment; fault tree analysis; risk control option



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1. Introduction

Globally, there are approximately 304 million international migrants, of whom 169 million participate in the labor market, accounting for 4.9% of the world's workforce [1]. Foreign (migrant) workers play a critical role in construction and manufacturing, as well as in primary industries such as agriculture and fisheries. However, multiple international reports have consistently highlighted their vulnerability to occupational accidents due to language and cultural barriers, limited safety training, and employment insecurity [2]. These issues are not confined to individual countries but represent shared challenges for global industrial and social sustainability [3].

Korea is no exception. As of 2024, the number of foreign residents in Korea stood at approximately 2.65 million, representing 5.2% of the total population, with around

567,000 holding employment qualifications, a figure that continues to increase annually [4]. Population aging and the reluctance of younger generations to enter primary industries have positioned foreign workers not as auxiliary labor but as a central workforce sustaining and enabling industry growth.

This trend is particularly evident in aquaculture. Global fish production reached a record high of 223.2 million tons in 2022, with aquaculture contributing 130.9 million tons (51%), surpassing capture fisheries for the first time [5]. In major aquaculture-producing countries such as Japan, Norway, and Chile, reports continue to highlight serious accidents involving foreign workers, often linked to limited experience, language barriers, and exposure to hazardous environments [6–10]. The most frequently cited risks in marine operations include falls from height, slips and falls, entanglement, struck-by incidents, and exposure to harmful environments [11]. A safety management report from Norway emphasized that mechanical hazards and work severity are central factors driving accidents, while accident patterns and severity vary depending on the maturity of the safety management system [12]. Recent reviews in occupational health and medicine have defined aquaculture as a multi-hazard occupation, stressing that basic control measures such as the use of personal protective equipment (PPE), repeated safety training, and the installation of equipment guards and emergency stop devices are directly linked to accident reduction [13]. Furthermore, structural factors like limited access to safety training due to language and cultural barriers and employment insecurity heighten the vulnerability of migrant workers in global fisheries and aquaculture supply chains [14,15].

Similarly, a recent global review by the Lloyd's Register Foundation [3] confirmed that mechanical entanglement and fall-related accidents remain the leading causes of injury and fatality in aquaculture, emphasizing that physical safeguards, emergency stop systems, and multilingual training are among the most effective preventive measures.

The aforementioned international evidence suggests that entanglement accidents among foreign workers and slip-and-fall or fall-from-height incidents among Korean workers are not solely attributable to individual factors. Instead, they reflect complex, interrelated issues spanning organizational aspects (training and procedures), equipment factors (guards and maintenance), and human elements (skills and behavior). In recent years, the international research community has also emphasized the importance of linking these safety factors with cost-based risk evaluation to improve management decision-making [16,17]. The Formal Safety Assessment (FSA) framework developed by the IMO provides a systematic approach to identifying and evaluating risks, formulating risk control options (RCOs), and performing cost-benefit analyses to support policy recommendations [18]. Huang et al. [19] further demonstrated that FTA-based frameworks remain a reliable method for diagnosing accident causes in marine operations, complementing other quantitative tools such as ETA and Bayesian networks. Its application has increasingly been explored in recent cost-benefit-based safety management studies within the maritime and fisheries sectors [11].

Despite the rapid growth of aquaculture production in Korea and the increasing reliance on foreign workers, systematic safety analyses of major accident types, such as slips and falls, entanglement, and struck-by incidents, remain limited within the Industrial Accident Compensation Insurance dataset [9]. Moreover, few studies have incorporated cost-based analyses to quantify the economic impact of accidents, even though such an evaluation is vital to prioritize preventive strategies effectively. Identifying the safety vulnerabilities of foreign workers and establishing tailored prevention strategies based on objective accident data are essential not only for enhancing industrial sustainability and workplace safety but also for reinforcing the resilience of global food supply chains.

This study combines two datasets—industrial accident insurance claims (268 Korean and 57 foreign workers) and field survey responses (193 Korean and 166 foreign workers)—to compare and analyze accident characteristics and safety perceptions by nationality in Korean aquaculture. By applying the IMO’s FSA framework together with FTA, this study develops a cost-based RCOs prioritization model linking accident data and economic evaluation. The findings are expected to contribute to sustainable safety management and international policy development in multicultural maritime and aquaculture industries.

2. Materials and Methods

2.1. Research Data

This study utilized approved Industrial Accident Compensation Insurance records (2018–2022) and field survey data on aquaculture workers in Korea. The insurance data involved the analysis of a total of 325 cases, comprising data on 268 Korean and 57 foreign workers. Key variables included nationality, accident type (entanglement, slip and fall, fall from height, struck by object, and others), and approved compensation amounts. The “others” category included accidents that occurred infrequently or were difficult to classify, such as drowning and vessel capsizing, exposure or contact with hazardous substances, repetitive-motion-related injuries, and contact with abnormal temperatures (e.g., heat or cold). Because all aquaculture workers in Korea are legally required to be covered by the Industrial Accident Compensation Insurance system, these cases represent the entire population of officially recognized occupational accidents within the aquaculture sector.

For the survey data, a total of 359 respondents participated, consisting of 193 Korean and 166 foreign workers. In addition to common questions, supplementary items were included for foreign workers to capture their experience with safety training and their specific requests for improvements. Although national statistics do not distinguish aquaculture workers by nationality, official records from Statistics Korea show that the total number of aquaculture workers remained relatively stable at approximately 5400–5500 persons per year during 2018–2022 [20]. Based on this baseline, our survey sample of 359 workers corresponds to roughly 6–7% of the estimated national workforce.

Moreover, because most Korean aquaculture farms are small-scale operations—typically employing fewer than ten workers per site—tasks tend to be shared across workers rather than divided by job specialization. As such, the proportional composition of Korean and foreign respondents in our survey reasonably reflects the organizational structure and labor characteristics of the industry. The composition of the study population is summarized in Table 1.

Table 1. Overview of the study population (n = number of cases; unit: %).

Data Type	Korean Workers	Foreign Workers	Total	Proportion
Insurance data	268	57	325	Korean (82.5)/Foreign (17.5)
Survey data	193	166	359	Korean (53.8)/Foreign (46.2)

Furthermore, national demographic trends were referenced as background data to contextualize the increasing reliance on foreign labor. Statistics from the Ministry of Justice [4] showed the number of foreign residents increased from 2,036,075 in 2020 (approximately 3.9% of the total population) to 2,650,783 in 2024 (5.2%). During the same period, the number of employed foreign workers rose from 452,297 to 566,961. Although the exact scale of aquaculture employment could not be verified, this trend reflects a nationwide structural shift in the labor force, with aquaculture labor following the same trajectory (Table 2).

Table 2. Status of the foreign workers in Korea (n = number of persons; unit: %).

Year	Total Foreign Residents	Share of Total Population	Employed Foreign Workers
2020	2,036,075	Approx. (3.9)	452,297
2024	2,650,783	Approx. (5.2)	566,961

2.2. Analytical Procedure

The analytical procedure for this study comprised the following steps: First, accident frequencies and average approved compensation amounts were calculated using the insurance data. Second, frequencies and averages for each survey item were computed using the survey data. Third, differences in distributions by nationality were tested using chi-square (χ^2) tests, while Likert-scale items were analyzed using independent-samples *t*-tests. Fourth, the average approved compensation amount was used as a reference indicator of accident severity. All statistical tests were conducted as two-tailed tests at a significance level of $\alpha = 0.05$. This level of significance was chosen to conclude statistical significance if the probability of the observed results occurring by chance was 5% or less.

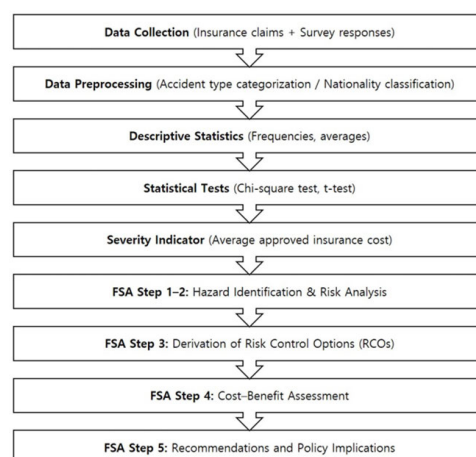
2.3. Application of the Formal Safety Assessment Framework

This study adopted the five-step FSA guidelines of the International Maritime Organization (IMO, MSC-MEPC.2/Circ.12) as the structural framework for the analysis [18]. The procedure was executed as follows: Step 1 involved the identification of accident types and indirect factors using insurance and survey data. Step 2 focused on the verification of nationality-based distribution differences and the execution of FTA. Step 3 was the derivation of RCOs. Step 4 entailed the cost–benefit analysis (B/C ratio) using approved compensation amounts. Finally, Step 5 involved the derivation of policy and industrial implications. The detailed procedure of Step 2 applying FTA was thoroughly described in our previous study [11], and in this study, the focus was extended to Step 3–4 for cost–benefit-based prioritization of RCOs.

2.4. Data Processing and Tools

Data processing was carried out using Microsoft Excel. Specifically, pivot tables were used to organize frequencies and distributions, and the CHISQ.TEST and T.TEST functions were applied to conduct the chi-square and *t*-tests. Approved compensation amounts were employed as unit accident costs and as the indicators for cost–benefit analyses of RCOs.

The indirect-to-direct cost ratio (*k*) was applied within a range of 0.5–1.0, reflecting production interruptions, replacement labor, and other associated losses. The overall research procedure is illustrated in Figure 1.

**Figure 1.** Flowchart of the research procedure.

3. Results and Discussion

3.1. Analysis of Insurance Data (2018–2022)

3.1.1. Distribution of Accident Types

Between 2018 and 2022, a total of 325 aquaculture accidents were approved under the Industrial Accident Compensation Insurance, including 268 cases involving Korean workers (82.5%) and 57 cases involving foreign workers (17.5%). Among Korean workers, slip and fall incidents were the most frequent, with 108 cases (40.3%), followed by entanglement with 53 cases (19.8%), and struck-by incidents with 40 cases (14.9%). In contrast, foreign workers experienced the highest proportion of entanglement accidents, with 22 cases (38.6%), followed by slip and fall with 14 cases (24.6%) and struck-by incidents with 11 cases (17.5%).

These findings indicate that accident patterns differed by nationality. Korean workers were more frequently affected by falls resulting from floor slipperiness or loss of balance, whereas foreign workers were more likely to be exposed to mechanical hazards such as entrapment or impact while handling machinery and equipment (Table 3). The accident classification system used in this study was standardized in accordance with the accident occurrence codes of the Korea Occupational Safety and Health Agency (KOSHA), which is consistent with the International Labor Organization’s (ILO) occupational accident classification principles [21].

It should be noted that task differentiation in Korean aquaculture is minimal. Most aquaculture farms operate as small-scale or family-run enterprises employing fewer than ten workers, where all personnel—regardless of nationality—typically engage in multiple overlapping tasks such as feeding, harvesting, equipment handling, and maintenance.

Table 3. Distribution of accident types by nationality (n = number of cases; unit: %).

Accident Type	Korean Workers	Foreign Workers	Total
Slip and fall	108 (40.3)	14 (24.6)	122 (37.5)
Entanglement	53 (19.8)	22 (38.6)	75 (23.1)
Struck by object	40 (14.9)	11 (19.3)	51 (15.7)
Fall from height	11 (4.1)	1 (1.8)	12 (3.7)
Others	56 (20.9)	9 (15.8)	65 (20.0)
Total	268 (100)	57 (100)	325 (100)

This structural characteristic is consistent with the smallholder aquaculture model widely observed in Asia, where farms are generally operated by limited manpower without clear job specialization [3,5].

Therefore, the observed differences in accident characteristics between Korean and foreign workers are unlikely to result from task assignment bias, but rather from disparities in safety training, language comprehension, and work experience.

3.1.2. Chi-Square (χ^2) Test

To examine whether the distribution of accident types differed significantly by nationality, a chi-square (χ^2) test was performed. This test evaluates whether the difference between the observed frequency (O) and the expected frequency (E) in each cell is statistically significant [22].

- Degrees of freedom (df): (number of rows − 1) × (number of columns − 1)
- Chi-square statistic (χ^2): $\sum (O - E)^2 / E$

- Effect size (Cramér's V): $\sqrt{(\chi^2/N(k-1))}$, where k is the smaller of the number of rows or columns

The results indicated $\chi^2(4, N = 325) \approx 14.8, p \approx 0.005$, confirming that the distribution of accident types differed significantly by nationality. The effect size (Cramér's V ≈ 0.21) corresponded to a small-to-medium association, suggesting that nationality explained approximately 4.6% of the variance in accident-type occurrence. These results support the robustness of the observed pattern beyond random variation.

To determine the contribution of individual cells to the chi-square statistic, standardized residuals (SR) were calculated. The analysis showed that the foreign worker-entanglement cell (SR $\approx +2.5$) exceeded the threshold, indicating that it contributed most strongly to the chi-square value (Table 4).

Table 4. Standardized residuals.

Accident Type	Korean SR	Foreign SR
Slip and fall	+0.7	−1.5
Entanglement	−1.1	+2.5
Struck by object	+0.2	−0.3
Fall from height	+0.3	−0.7
Others	+0.0	+0.0

These results suggest that Korean workers face relatively higher risks of falls caused by floor slipperiness and balance loss, while foreign workers experience a higher incidence of entanglement accidents involving machinery and equipment. Accordingly, fall- and height-prevention measures would be particularly necessary for Korean workers, whereas safety guard installation and enhanced multilingual safety training are critical strategies for foreign workers.

3.1.3. Analysis of Approved Compensation Amounts

The characteristics of approved compensation amounts by accident type were compared across nationalities (Table 5). Approved compensation was defined as the sum of medical care benefits, temporary disability benefits, and permanent disability benefits under the Industrial Accident Compensation Insurance Act [23].

Table 5. Statistics of approved compensation amounts by accident type and nationality (n = number of cases; unit: USD).

Nationality	Accident Type	n	Mean Approved Compensation (USD)	Standard Deviation (USD)
Korean	Slip and fall	108	9203.26	12,862.57
	Entanglement	53	20,153.81	33,932.75
	Struck by object	40	11,048.53	15,896.21
	Fall from height	11	35,045.27	61,056.33
	Others	56	16,401.38	30,769.62
Foreign	Slip and fall	14	2135.78	2494.52
	Entanglement	22	8134.38	11,089.60
	Struck by object	11	2043.34	2325.71
	Fall from height	1	4855.72	—
	Others	9	8174.63	17,392.32

(a) Approved Compensation by Accident Type and Severity

In the Korean group, falls from height recorded the highest average compensation at USD 35,045 per case, followed by entanglement (USD 20,154), struck-by incidents (USD 11,049), and slip and fall accidents (USD 9203). In the foreign group, entanglement had the highest average compensation (USD 8134), followed by falls from height (USD 4856), slip and fall accidents (USD 2136), and struck-by incidents (USD 2043). These results show that accidents such as machinery entrapment and falls from height, which cause more severe injuries, are associated with substantially higher per-case costs. By contrast, slip and fall and struck-by incidents had relatively low average compensation amounts, suggesting that these often result in minor injuries. The “others” category included rare but high-cost accidents such as drowning and vessel capsizing. Because of their heterogeneous nature, these cases were excluded from subsequent comparative analyses.

(b) Comparison of Approved Compensation by Nationality

Overall, the average compensation for Korean workers was higher than that for foreign workers. However, this does not necessarily indicate that accidents among Korean workers were intrinsically more severe. The lower compensation for foreign workers is likely attributable to structural and institutional factors, such as the higher prevalence of short-term or contract employment, shorter employment duration, lower wage levels, and differences in insurance assessment methods [24]. Therefore, the differences in average amounts by nationality should be interpreted within a structural and institutional context rather than as a reflection of medical severity.

3.2. Survey Analysis

3.2.1. Characteristics of Survey Respondents

The survey was conducted among 359 aquaculture workers. By nationality, 193 respondents (53.8%) were Korean, and 166 respondents (46.2%) were foreign. All participants had recent work experience in aquaculture for one year.

Age Distribution

Among Korean respondents, 30.1% were in their 50s and 34.7% were aged 60 or older, indicating a pronounced trend toward an aging workforce, with approximately 65% aged 50 or above. In contrast, 51.2% of foreign respondents were under 30 years old, and 43.4% were aged 30–39, meaning approximately 95% (94.6%) of the foreign respondents were under 40. This reflects a generational contrast in which Korean workers are predominantly older, long-term employees, whereas foreign workers consist largely of younger, newly recruited labor.

Length of Service and Safety Training

For Korean respondents, the survey did not include detailed questions regarding continuous service. However, previous studies have reported that many Korean aquaculture workers have worked for more than 10 years [11]. Consequently, the Korean group was interpreted as comprising mainly long-term employees. For foreign respondents, continuous service was measured based on current employment. Since Korea’s employment system is structured around three-year contracts, approximately 30% of foreign respondents had been employed for 1–3 years, while 40% had more than 3 years of service. This indicates that foreign workers are not limited to short-term, rotating labor but include a significant proportion who continue employment through contract renewals.

Regarding safety training, 81% of Korean workers reported receiving formal training, compared with 47% of foreign workers, highlighting language and communication barriers as major constraints on training participation.

Table 6 summarizes the key demographic and safety-training characteristics of Korean and foreign aquaculture workers.

Table 6. General characteristics of survey respondents by nationality (n = number of persons; unit: %).

Category	Korean Workers	Foreign Workers	Key Observation
Sample size	193 (53.8)	166 (46.2)	–
Age $\leq$ 39 years	26 (13.5)	157 (94.6)	Foreign workforce is much younger.
Age $\geq$ 50 years	125 (64.8)	1 (0.6)	Korean workforce is aging.
Continuous service $\geq$ 3 years	193 (100.0)	66 (39.8)	Longer tenure among Koreans.
Received safety training before work	–	45 (29.6) *	Limited pre-employment training for foreigners.
Requested additional safety training	–	95 (62.5) *	Strong demand among foreigners.
Primary perceived risk	Slip and fall (36.3)	Slip and fall (41.6)	Consistent across both groups.
Second-highest perceived risk	Entanglement (20.7)	Struck by object (26.5)	Machinery-related risks are higher for foreigners.

Asterisks () indicate items surveyed only among foreign respondents. Percentages are based on valid responses. Rounded values may not sum to exactly 100 due to rounding.*

(Detailed cross-tabulations of individual survey items are provided in Supplementary Tables S1–S3.)

3.2.2. Perceptions of Risk Factors

The survey revealed distinct differences in perceived accident risks by nationality (Table 6).

For Korean workers, slip and fall was perceived as the most significant risk (36.3%), followed by entanglement (20.7%), fall from height (19.2%), and being struck by object (13.0%). This distribution corresponds with the demographic structure noted in Section 3.2.1, where the majority of respondents were aged 50 years or older. Aging-related declines in balance control and musculoskeletal strain appear to elevate the perceived risk of falls, such as slips and falls from height.

For foreign workers, slip and fall was also perceived as the greatest risk (41.6%), followed by being struck by object (26.5%) and entanglement (17.5%). However, the insurance data showed that actual accidents among foreign workers occurred more frequently through entanglement and struck-by incidents. This discrepancy between perceived risks and actual accident patterns suggests that foreign workers may not fully recognize the hazards of machinery entrapment and struck-by incidents.

In summary, while Korean workers are primarily vulnerable to falls due to aging and musculoskeletal limitations, foreign workers face elevated risks related to machinery and equipment as a result of limited experience, language barriers, and insufficient safety training. Nevertheless, workers' own perceptions of risk only partially aligned with actual accident patterns. Safety training should therefore go beyond emphasizing general hazards and instead be tailored to reflect objective accident data, such as insurance records. For foreign workers in particular, training programs should be designed to heighten awareness of frequent and high-cost risks, notably entanglement and struck-by incidents.

3.3. Fault Tree Analysis

The survey initially followed the traditional 4 M framework (Man, Management, Machine, and Environment). For analytical purposes, however, responses were reclass-

sified according to the Human Element framework, consisting of People Factors (PF), Organization at the farm site (ORG), Facility and Equipment (F&E), Working/Living Conditions (WLC), Shore-side Management (SSM), and External Environment (EXT), in order to conduct the FTA [25,26].

The Human Element approach provides the advantage of structuring accident causation beyond individual errors to include organizational, equipment, and environmental factors, making it well-suited for risk assessment in the fisheries and maritime sectors [26].

Respondents were allowed to select multiple causes. For example, the 70 Korean respondents who identified slip and fall as a risk generated a total of 280 detailed responses ($70 \times 4 = 280$). The unit of analysis in this FTA was therefore the number of detailed responses, rather than the number of individual respondents. The logical gates in the FTA were set as OR gates, reflecting field conditions where a single causal factor can be sufficient to trigger an accident [27].

To avoid unnecessary duplication, only the primary and secondary factors were presented in this study. A fully expanded and detailed FTA structure was already developed and empirically validated in our previous research on aquaculture worker safety [11].

Since the main objective of the present study is the cost-based prioritization of RCOs rather than complete causal reconstruction, a simplified FTA model was applied while maintaining analytical validity and practical relevance.

Summary of Fault Tree Analysis Results

The FTA identified the relative contributions of each Human Element category to the major accident types for Korean and foreign workers.

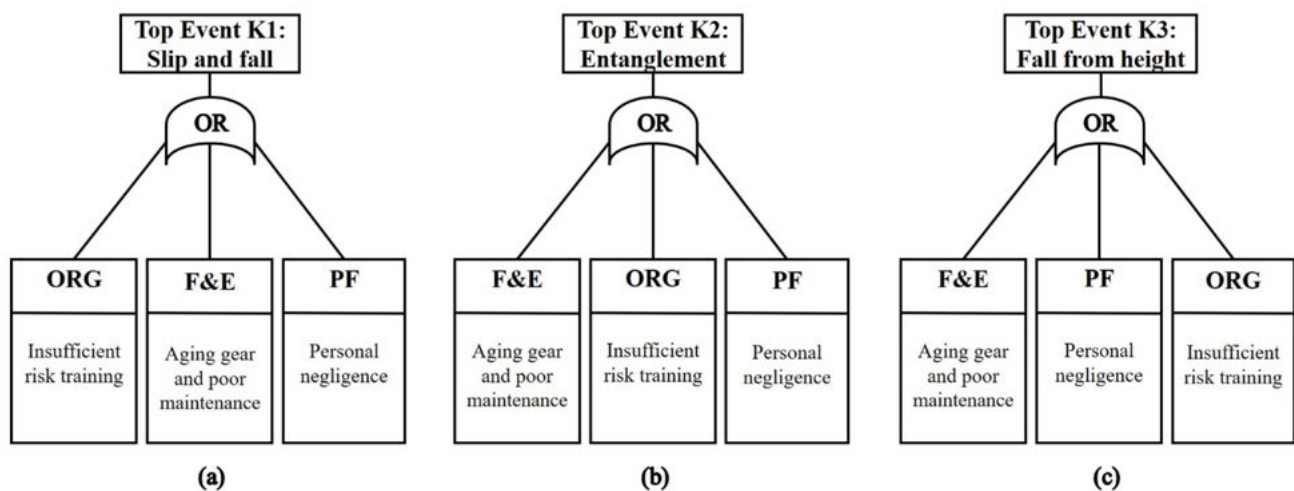
Table 7 presents the results for Korean workers, and Table 8 shows those for foreign workers. Detailed event-level decompositions used for FTA construction are provided in the Supplementary Tables S4–S8, and representative fault trees are shown in Figures 2 and 3.

Table 7. Korean workers—Summary of fault tree analysis results by accident type (n = frequency of detailed responses in the fault tree analysis; unit: %).

Accident Type	Human Element	Major Causes (Example)	Frequency	Proportion
Slip and fall	PF	Personal negligence, lack of PPE, poor posture, lack of skill	64	22.9
	ORG	Insufficient risk training, safety neglected in daily work	71	25.4
	F&E	Aging gear, faulty machinery, missing safety barriers	70	24.9
	WLC	Messy/cluttered deck, narrow workspace, poor communication	38	13.6
	SSM	No work guidelines, safety rules not posted	20	7.1
	EXT	Harsh sea/weather conditions	17	6.1
Entanglement	PF	Personal negligence, lack of PPE, poor posture, lack of skill	32	20.0
	ORG	Insufficient risk training, safety neglected in daily work	39	24.4
	F&E	Aging gear, faulty machinery, missing safety barriers	40	25.0
	WLC	Messy/cluttered deck, narrow workspace, poor communication	22	13.8
	SSM	No work guidelines, safety rules not posted	20	12.5
	EXT	Harsh sea/weather conditions	7	4.4
Fall from height	PF	Personal negligence, lack of PPE, poor posture, lack of skill	32	21.6
	ORG	Insufficient risk training, safety neglected in daily work	31	20.9
	F&E	Aging gear, faulty machinery, missing safety barriers	37	25.0
	WLC	Messy/cluttered deck, narrow workspace, poor communication	17	11.5
	SSM	No work guidelines, safety rules not posted	18	12.2
	EXT	Harsh sea/weather conditions	13	8.8

Table 8. Foreign workers – Summary of fault tree analysis results by accident type (n = frequency of detailed responses in the fault tree analysis; unit: %).

Accident Type	Human Element	Major Causes (Example)	Frequency	Proportion
Slip and fall	PF	Personal negligence, lack of PPE, poor posture, lack of skill	61	22.1
	ORG	Insufficient risk training, safety neglected in daily work	77	27.9
	F&E	Aging gear, faulty machinery, missing safety barriers	69	25.0
	WLC	Messy/cluttered deck, narrow workspace, poor communication	20	7.2
	SSM	No work guidelines, safety rules not posted	40	14.5
	EXT	Harsh sea/weather conditions	9	3.3
Entanglement	PF	Personal negligence, lack of PPE, poor posture, lack of skill	29	25.0
	ORG	Insufficient risk training, safety neglected in daily work	29	25.0
	F&E	Aging gear, faulty machinery, missing safety barriers	29	25.0
	WLC	Messy/cluttered deck, narrow workspace, poor communication	6	5.2
	SSM	No work guidelines, safety rules not posted	15	12.9
	EXT	Harsh sea/weather conditions	8	6.9
Struck by object	PF	Personal negligence, lack of PPE, poor posture, lack of skill	44	25.0
	ORG	Insufficient risk training, safety neglected in daily work	48	27.3
	F&E	Aging gear, faulty machinery, missing safety barriers	44	25.0
	WLC	Messy/cluttered deck, narrow workspace, poor communication	8	4.5
	SSM	No work guidelines, safety rules not posted	22	12.5
	EXT	Harsh sea/weather conditions	10	5.7

**Figure 2.** Fault tree analysis results for Korean workers: (a) slip and fall (K1), (b) entanglement (K2), and (c) fall from height (K3).

Both groups showed that PF, ORG, and F&E factors combined to cause accidents, but the emphasis differed between them.

For Korean workers, exposure to slip and fall or fall-from-height accidents was greater, reflecting the high proportion of older workers. Aging equipment (F&E) and procedural deficiencies (ORG) further amplified the risk of severe accidents such as falls from height. Conversely, among foreign workers, a higher proportion of entanglement and struck-by accidents was observed, with responses emphasizing language barriers and insufficient training (ORG) alongside weaknesses in equipment safety, such as missing guards (F&E).

Accordingly, fall and slip-related engineering protections combined with reinforcement of permit-to-work (PTW) and lockout/tagout (LOTO) procedures appear most appropriate for Korean workers, whereas the priority for foreign workers lies in retrofitting

machinery with guards, interlocks, and emergency stop systems (E-stop), along with multilingual SOPs and repeated training.

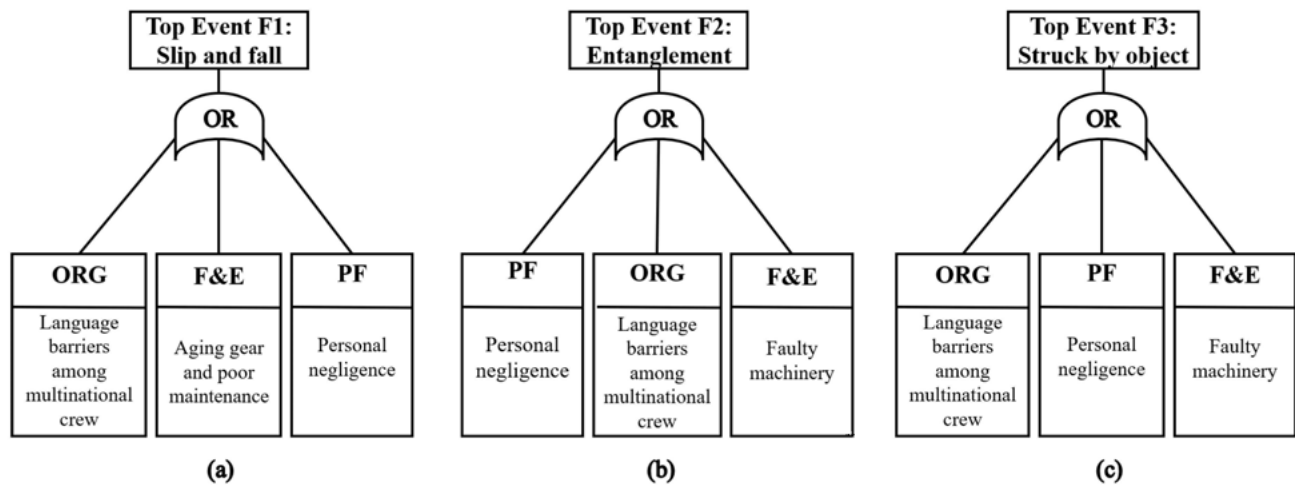


Figure 3. Fault tree analysis results for foreign workers: (a) slip and fall (F1), (b) entanglement (F2), and (c) struck by object (F3).

3.4. Cost–Benefit Analysis

Based on the results of the FTA, this section quantitatively evaluated the scale of economic losses associated with each accident type using insurance approval data. The raw data employed were the same as the approved compensation statistics presented in Section 3.1.3. While Section 3.1.3 focused on average amounts per case, the present analysis examined the total approved amounts by accident type to clarify the cost structure.

3.4.1. Cost by Accident Type

The 325 approved cases (268 involving Korean workers and 57 involving foreign workers) were reaggregated by accident type on the basis of total approved compensation (Table 9). The “others” category was presented only for descriptive reference, as it combined heterogeneous causes, and was excluded from the subsequent prioritization analysis in Section 3.5.

The results showed that in the foreign worker group, entanglement accidents accounted for more than half of the total approved costs, indicating that economic losses were concentrated in mechanical hazards. In contrast, for Korean workers, falls from height and entanglement represented the largest cost shares. Although slip and fall accidents were the most frequent, their relatively low per-case cost limited their overall contribution to total costs. These results provided the foundation for calculating the importance index (P) in Section 3.5 and for designing tailored RCOs with a high cost-effectiveness ratio.

Table 9. Total approved compensation by accident type (n = number of cases; unit: USD).

Accident Type	Korean Cases	Korean Cost	Foreign Cases	Foreign Cost
Slip and fall	108	994,000	14	30,000
Entanglement	53	1,068,000	22	179,000
Struck by object	40	442,000	11	23,000
Fall from height	11	386,000	1	5000
Others (miscellaneous)	56	919,000	9	74,000
Total	268	3,809,000	57	310,000

3.4.2. Cost Including Indirect Costs

Accurate estimation of the economic losses from occupational accidents requires consideration not only of direct costs, such as approved insurance compensation, but also of indirect costs. According to the Ministry of Employment and Labor's industrial accident cost estimation (2021), indirect costs—including production interruptions, replacement labor—are estimated to amount to approximately 0.5–1.0 times the direct costs [28]. To account for this, the following estimation formula was applied:

$$\text{Total cost} = \text{Direct cost} \times (1 + k)$$

where k: ratio of indirect to direct costs (conservative estimate k = 0.5, upper-bound estimate k = 1.0)

Applying this formula, the estimated total socio-economic losses by accident type, including indirect costs, are presented in Table 10.

Table 10. Estimated total accident costs, including indirect costs (unit: USD).

Group	Direct Cost	Total Cost (k = 0.5)	Total Cost (k = 1.0)
Korean	3,809,000	5,714,000	7,618,000
Foreign	310,000	465,000	620,000
Total	4,119,000	6,179,000	8,238,000

The total loss was estimated at a minimum of USD 6.18 million and a maximum of USD 8.24 million, representing an increase of approximately 1.5–2 times compared with direct costs alone. This finding demonstrates that RCOs can generate benefits beyond reducing insurance payments, directly contributing to productivity maintenance, workforce stability, and reductions in broader social costs. Furthermore, these estimates provide the economic basis for calculating the importance index (P) in Section 3.5 and determining the priority of RCOs [18].

3.5. Recommendations and Policy Implications

Building on the quantified results of accident frequency and costs (both direct and indirect) in Section 3.4, this section presents the importance index (P) for each accident type and, based on these findings, proposes tailored RCOs with high cost-effectiveness. All numerical data in Tables 11 and 12 originate from the verified insurance dataset described in Section 3.1.3.

Table 11. Importance index (P) of accident types (n = number of cases; units: USD and %).

Accident Type	Korean Cases (n)	Korean Cost (USD)	P (%) Korean	Foreign Cases (n)	Foreign Cost (USD)	P (%) Foreign
Slip and fall	108	994,000	34.4	14	30,000	12.7
Entanglement	53	1,068,000	37.0	22	179,000	75.5
Struck by object	40	442,000	15.3	11	23,000	9.7
Fall from height	11	386,000	13.4	1	5000	2.1
Subtotal	212	2,890,000	100.0	48	237,000	100.0

Table 12. Proposed core Risk Control Options.

ID	RCO (Concise)	Target Workforce	Main Accident Type	Primary HE Axis	Mechanism (One-Line)	Cost Level *	KPI Examples	Assumed Reduction (%) †
R1	Guarding and interlocks retrofit + E-stop	Foreign	Entanglement	F&E	Physical separation/auto-stop	High	% guarded points, E-stop test pass rate	20–40
R2	Multilingual SOPs + pictogram training	Foreign	Entanglement	ORG	Language-neutral procedures and daily briefings	Low–Med	Training coverage, quiz score	10–25
R3	Fall-protection system upgrade (rails, lifelines)	Korean	Fall from height	F&E	Engineering controls for work-at-height	High	% compliant edges, harness use rate	20–40
R4	Permit-to-Work (PTW) and Lockout/Tagout (LOTO)	Korean	Fall from height	ORG/SSM	Formal authorization and energy isolation	Low–Med	PTW compliance, LOTO violations	10–25

* Cost level: Relative depending on site size and scope; † Assumed reduction: Applied in scenario analysis (Section 3.5.3).

3.5.1. Importance of Accident Types

From the 325 approved insurance cases (268 involving Korean workers and 57 involving foreign workers), cases categorized as “others” were excluded. The importance index P was therefore calculated using 212 Korean and 48 foreign cases (Table 11).

$$P_i = \frac{C_i}{\sum C_i} \times 100$$

where C_i = total approved compensation (USD) for accident type i .

The results were as follows.

Korean workers: Although entanglement accounted for the largest share in absolute terms (37.0%), the accident type with the highest cost per case was fall from height. Despite only 11 cases, total costs reached USD 386,000, indicating that each event carried the highest unit cost among all accident types. This highlights the significant likelihood of severe or fatal outcomes. Consequently, fall from height was designated as the primary accident type for Koreans in the subsequent cost–benefit and policy recommendations.

Foreign workers: Entanglement accounted for 75.5% of total costs, overwhelmingly dominating both frequency and cost. Slips and falls (12.7%) and being struck by objects (9.7%) contributed far less in comparison. The Fall from height category was excluded from comparison due to the limited number of cases.

These results demonstrate that Korean workers face risks that are dispersed across multiple tasks but concentrated in severe accidents involving falls, whereas foreign workers are heavily engaged in high-risk mechanical tasks where entanglement is predominant.

3.5.2. Risk Control Options

By combining the Human Element-based FTA findings with the importance index P , tailored RCOs were proposed for each group, emphasizing cost-effectiveness (Table 12).

For foreign workers, the key accident type was entanglement, primarily driven by mechanical hazards (F&E) and organizational factors like language barriers and insufficient training (ORG); thus, the most effective strategies would be a combination of machinery retrofitting with guarding, interlocks, and emergency stop systems (R1), and the implementation of multilingual SOPs supported by pictogram-based training (R2).

These strategies integrate engineering improvements with multilingual procedures and training. The IMO’s FSA guidelines [18] and the EU Machinery Directive [29] require guarding, interlocks, and emergency stops on hazardous machines, while ILO and

NIOSH guidelines for multicultural workplaces [30,31] emphasize multilingual SOPs and pictogram-based training as essential preventive measures.

For Korean workers, the key accident type was fall from height, which was primarily caused by facility and equipment issues, specifically the absence of adequate fall-protection systems (F&E), and organizational/shore-side management deficiencies, such as insufficient Permit-to-Work (PTW) and energy isolation procedures (ORG/SSM). Consequently, effective risk reduction strategies involve upgrading fall-protection systems (R3) and rigorously implementing standardized PTW and Lockout/Tagout (LOTO) procedures (R4). These strategies combine engineering controls with institutionalized management systems. IMO's FSA guidelines [18], the CCPS LOPA manual [32], and NIOSH safety culture guidelines [31] all highlight PTW and LOTO procedures as critical risk control measures for high-risk tasks.

Meanwhile, slip and fall and struck-by accidents, while relatively frequent, involve low unit costs. For these types, low-cost, broad-scope supplementary measures are appropriate, such as anti-slip flooring, housekeeping standards, and tool tethering [10].

3.5.3. Scenario-Based Prioritization and Sensitivity Analysis

To assess the economic feasibility and implementation priority of each RCO, the annual expected cost saving (AEC) and a budget constraint equation were applied. The sum of initial capital expenditure (Capex) and annual operating expenditure (Opex) was set not to exceed the available budget (B).

$$AEC = \sum r_i \times \gamma_i \times C_i$$

$$\Sigma(Capex_i + Opex_i) \leq B$$

where the following applies:

γ_i = expected reduction rate;

r_i = coverage/compliance coefficient;

C_i = total cost of the target accident type (USD);

$Capex_i, Opex_i, B$ = defined as above.

The expected reduction rate (r value) for the proposed risk control options was determined based on established safety guidelines: engineering and physical barrier measures (R1,R3) were assigned a higher reduction range of 20–40%, while procedural and training measures (R2,R4) were assigned a range of 10–25%. These ranges referenced practical values repeatedly cited in IMO's FSA guidelines [18], NIOSH safety culture guidelines [31], and the CCPS Layer of Protection Analysis (LOPA) manual [32].

The coverage/compliance coefficient (γ value) is a factor calculated by multiplying site-level implementation coverage by compliance rates over the short- to medium-term. The empirical range of 0.7–0.8 commonly cited in international safety culture and risk management guidelines was applied [33,34].

Sensitivity analyses were performed under conservative, neutral, and aggressive scenarios by varying these values. The priority order of RCOs remained consistent across scenarios.

For foreign workers, R1 followed by R2 showed the highest AEC contributions. When implemented together, these measures most effectively reduced the entanglement-related costs (63.5%).

For Korean workers, R3 followed by R4 emerged as the top priorities, effectively reducing fall-from-height risks and preventing secondary losses. By contrast, slip and fall and struck-by incidents, with lower unit costs, were more suitable for low-cost, broad-based supplementary measures.

3.5.4. Research Contributions and Limitations

This study proposed a cost-based RCO prioritization model that integrates approved insurance compensation with estimated indirect costs, thereby quantitatively incorporating economic evaluation and cost–benefit analysis into aquaculture safety management, where such approaches have been limited.

However, there are some limitations as follows.

- Insurance data primarily reflected direct costs, and the indirect cost coefficient (k) was adopted from national industrial accident statistics.
- Detailed indirect costs, such as long-term health impacts and production downtime specific to each site, were not included.

Future research should refine the cost-based RCO model by incorporating more granular indirect costs and field-level data categorized by task and equipment, thereby enhancing precision and practical applicability.

4. Conclusions

This study integrated 325 approved cases from the Industrial Accident Compensation Insurance between 2018 and 2022 (268 involving Korean workers and 57 involving foreign workers) with field survey data and FTA to quantitatively identify accident characteristics and cost structures among Korean and foreign aquaculture workers. The key findings were that among foreign workers, accidents and associated costs were concentrated in high-risk tasks involving entanglement, while among Korean workers, slips and falls were the most frequent accident type. However, falls from height were identified as the most critical category because they had the highest per-case compensation cost and severity, indicating a greater likelihood of serious or fatal injuries. Based on these results, group-specific RCOs were proposed: For foreign workers, R1 (guarding and interlocks retrofit with emergency stop systems) and R2 (multilingual SOPs and pictogram-based training); and for Korean workers, R3 (fall-protection system upgrade) and R4 (institutional measures such as Permit-to-Work (PTW) and Lockout/Tagout (LOTO)). These strategies consistently demonstrated cost-saving effects across conservative, neutral, and aggressive scenarios, confirming their effectiveness. Methodologically, this study developed a cost-based RCO prioritization model by combining insurance approval data with indirect cost estimates, thereby quantitatively incorporating economic evaluation into aquaculture safety management, where such analyses have previously been limited. The model provides a practical foundation for establishing cost–benefit-driven safety policies in the multicultural and multi-hazard environment of aquaculture. The proposed cost-based RCO model can be enhanced through future research, including more detailed categories of indirect costs, such as production downtime, replacement labor, and long-term health impacts, and field-level data differentiated by the work environment.

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