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Off-Site Emergency Response Plans at Chemical Accidents in South Korea

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Abstract: The Chemical Substances Control Act emphasizes the importance of proactive planning for chemical accident prevention and response, requiring facilities handling hazardous chemicals to develop and submit comprehensive plans in compliance with regulatory standards. Among these measures, the designation of chemical accident evacuation sites is considered a critical step to protect local residents and mitigate the impact of accidents. Despite the significance of evacuation site planning, existing research has primarily focused on the general conditions and locations of evacuation sites, with limited attention to their selection process and safety evaluation. This study aims to bridge this gap by evaluating the suitability of evacuation site locations through detailed risk assessments. Using tools such as KORA and ALOHA, the study analyzes the impact range under seasonal meteorological conditions. The limitations of current evacuation sites were assessed, and additional sites were proposed, considering the number of evacuees able to travel on foot during emergencies. The study highlights the importance of selecting evacuation sites based on seasonal weather conditions and provides actionable recommendations to improve public safety and minimize risks during chemical accidents. The findings of this study are expected to contribute to the advancement of emergency response systems, promoting a safer and more resilient environment for both local communities and industrial facilities.

Keywords: chemical accident; emergency response plan; chemical accident evacuation location; risk assessment; KORA; ALOHA

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1. Introduction

In September 2012, a hydrofluoric acid gas leak accident in Gumi caused the deaths of five workers at the site, along with reports of health issues among nearby residents and livestock fatalities, resulting in significant human and material damage [1–3]. Following the accident, ongoing research and national-level efforts were initiated to improve chemical accident responses, highlighting issues with emergency responses and identifying actions that required improvement [4,5]. This social backdrop prompted a comprehensive revision of the Chemical Substances Control Act, which included the implementation of regulations mandating the development of chemical accident prevention and management plans, as well as emergency response plans for chemical-handling facilities [6].

The chemical accident prevention and management plan aims to establish a community-level chemical accident response system by informing the local community about hazardous chemical information and emergency response measures implemented by facilities [7,8].

Evacuation sites, an essential notification element in the event of an accident, are critical for preventing casualties from chemical leaks and ensuring the safety of local residents. This is because chemical leaks have a significant impact on nearby businesses and residents [5,9]. Additionally, designating evacuation sites in advance can minimize confusion and facilitate prompt evacuations during chemical accidents. Based on this rationale, research into emergency evacuations during chemical accidents should be conducted. Furthermore, because wind direction has a significant impact on the dispersion and movement of chemical substances, rational safety measures should consider meteorological conditions [10].

To select suitable evacuation sites, an approach that considers wind direction and the surrounding geography is required, rather than relying on uniform site selection methods. The manual for drafting chemical accident prevention and management plans recommends designating at least two evacuation shelters in different directions based on the wind direction [11]. However, an analysis of ten current chemical accident evacuations revealed cases in which evacuation shelters were uniformly designated in the same direction. To reduce casualties in chemical accidents, it is essential to select evacuation shelters that reflect seasonal weather conditions and wind direction patterns.

Previous research on chemical accidents has primarily focused on technical and managerial prevention measures, as well as legal or institutional improvements to prevent accidents [12–16]. Although studies on accident response and community safety have been conducted, they have primarily focused on target selection, effective notification methods, and strategies to enhance public notification [17–23].

While existing studies on evacuation site selection consider wind direction, comprehensive research incorporating seasonal weather conditions and wind patterns to determine the best locations for evacuation during chemical accidents is still lacking [4,24–28].

This study reviews current chemical accident evacuation sites to determine whether they are appropriately located and capable of protecting local residents by considering meteorological conditions such as wind direction and speed. Furthermore, additional evacuation sites have been proposed as part of the improvement measure. The results and proposed improvements from this study are expected to contribute to strengthening emergency response systems during chemical accidents.

2. Theoretical Background and Methods

2.1. Related System

The community notification system under the Chemical Accident Prevention and Management Plan was designed to ensure the safety of local residents and enable a prompt response in the event of a chemical accident by providing the local community with information related to chemicals handled by facilities [7,8,11].

The workflow of the Chemical Accident Prevention and Management Plan is shown in Figure 1. The purpose of this system is to provide local residents with information on the types and quantities of hazardous chemicals handled by nearby facilities, as well as response plans in the event of an accident, so that they can plan for potential risks. Certain details are disclosed to the community to achieve this goal. The disclosed information includes facility details, a list of hazardous chemicals and their key hazards, the overall impact range of accident scenarios, emergency contact systems, methods for issuing evacuation alerts, and designated evacuation sites and procedures during accidents.

Among the information disclosed, evacuation sites play an important role in ensuring the safety of residents during a chemical spill.

When selecting evacuation sites for chemical accidents, it is recommended to designate at least two sites considering wind direction [11]. This is because hazardous chemicals can spread along the wind during chemical accidents, and providing evacuation sites in multiple

directions ensures that residents can evacuate safely. However, an analysis of evacuation sites designated for 10 facilities revealed that the evacuation sites were uniformly designated in the same direction, as summarized in Table 1.

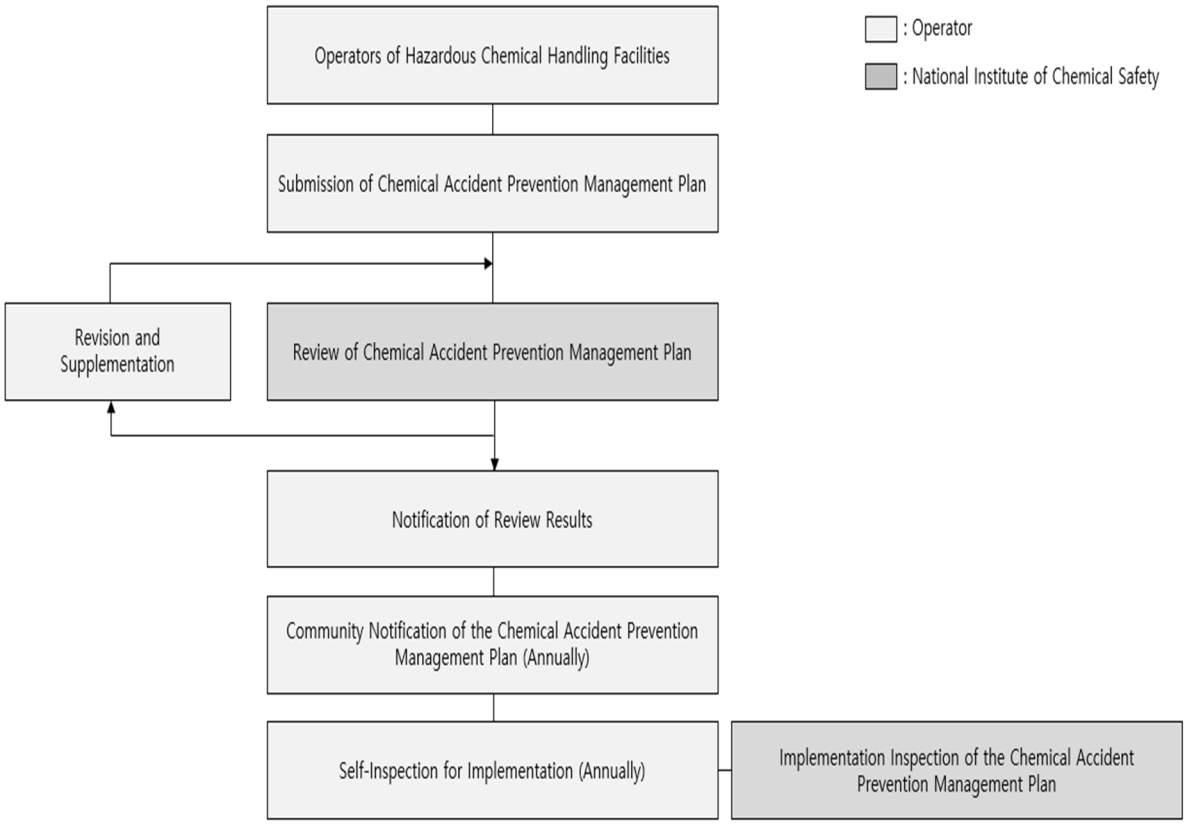


Figure 1. Procedures for the chemical accident prevention management plan (operator-centered).

Table 1. Analysis of current chemical accident shelter locations.

Workplace	Current Number of Chemical Accident Evacuation Sites	Current Locations of Chemical Accident Evacuation Sites	Issues
a	5	NW	All located in the northwest direction
b	2	SE	All located in the southeast direction
c	3	SE	All located in the northwest
d	1	SE	Only one designated
e	2	E	All located in the east
f	2	NE	All located in the northeast
g	2	SW	All located in the southwest
h	2	NE	All located in the northeast
i	3	N	All located in the north
j	3	S	All located in the south

2.2. Selection of Target Substances

Approximately 40,000 chemical substances are currently used in South Korea, and their variety and applications are continuously expanding [29,30].

Among them, the number of facilities handling styrene monomers has significantly increased, from 1191 in 2014 to 1673 in 2020, due to the rising demand for chemical products such as plastics and synthetic rubber (Figure 2) [31]. Styrene monomers are produced through the reaction of ethylene and benzene, in which ethylbenzene is oxidized and

dehydrogenated to form styrene, followed by polymerization initiated by various initiators. The heat of polymerization generated during this process is approximately 16.7 kcal/mol, and if the exothermic reaction is not adequately controlled, there is a risk of explosion at high temperatures. In particular, styrene monomers react with oxygen in the air during oxidation, releasing heat and light, which increases the risk of fire and explosion. Overexposure can cause skin and respiratory irritation, leading to health issues. Additionally, styrene is a volatile organic compound (VOC) that rapidly evaporates into the atmosphere, contributing to environmental pollution.

Therefore, this study selected styrene monomer as the target substance due to its increasing usage and inherent risk of explosion.

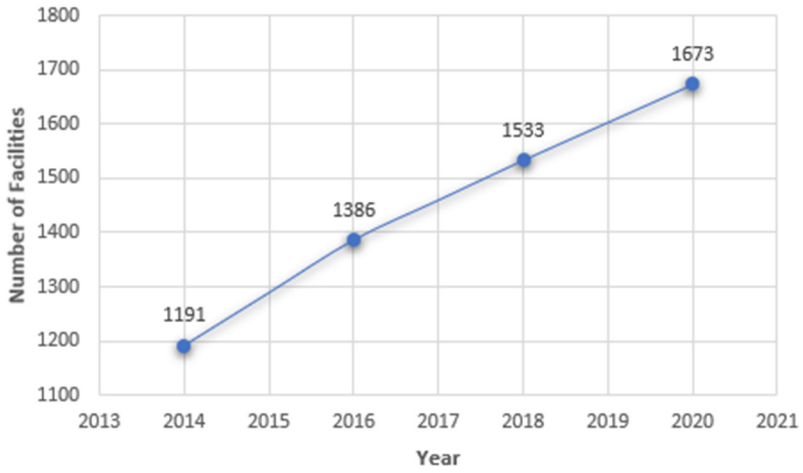


Figure 2. Facility trend of styrene monomer-handling companies.

2.3. Major Accident Cases Involving Styrene Monomer

Styrene monomer has seen a global increase in handling volume due to the rising demand for chemical products such as plastics and synthetic rubber. It is a particularly high-risk substance prone to accidents caused by polymerization reactions and temperature control failures. To better understand the risks associated with styrene monomer, domestic and international accident cases were investigated.

In May 2020, a styrene monomer leak from a storage tank at a factory in southern India resulted in 13 deaths and the hospitalization of approximately 1000 people. The causes were attributed to poor design, malfunctioning alarms, and ignored warnings [32,33]. In May 2019, a leak occurred during refining at the Daesan SM plant in South Korea. Prolonged storage of high-concentration styrene mixtures causes polymerization inhibitor deactivation, which accelerates self-polymerization [34–36]. In August 2011, runaway polymerization occurred during a trial run after maintenance in Nam-gu, Ulsan, causing injuries and severe equipment damage. The causes included temperature control failure and delayed ethylbenzene injection [37,38]. In August 2005, a styrene leak from a railroad tank car in Cincinnati, Ohio, caused evacuations within a 0.5 mi radius and temporarily closed an airport due to pressure buildup from a polymerization reaction [39,40].

Repeated styrene monomer leak accidents in South Korea, the United States, India, and other parts of the world highlight common issues, such as polymerization reactions and temperature control failures. These accidents underscore the importance of implementing strict safety and management measures (Table 2).

Table 2. Styrene monomer accident cases.

Date of Accident (Year, Month)	Accident Overview	Damage
20.05	Styrene Monomer Leak Accident Caused by Design Flaws and Non-Compliance with Safety Procedures	13 Deaths, 1000 Injuries
19.05	Styrene Monomer Leak Accident Due to Prolonged Storage	Approximately 4000 Injuries (Primarily Hospitalized for Symptoms Such as Headaches and Vomiting)
11.08	Explosion Accident Caused by Process Control Failure and Non-Compliance with Safety Procedures	3 Deaths, 4 Injuries
05.08	Styrene Monomer Leak in a Railroad Tank Car Due to Polymerization Reaction	Evacuation of Residents Within 0.5 Miles, Airport Closure

2.4. KORA and ALOHA

Facilities utilize the Korea Offsite Risk Assessment Support tool (KORA) to select evacuation sites in the event of a chemical accident (version 5, National Institute of Chemical Safety, Cheongju, Republic of Korea). KORA evaluates the impact range of potential fires, explosions, and toxic dispersion accidents from handling facilities, while also analyzing accident frequency to calculate the risk level of accident scenarios [41,42]. However, KORA does not account for wind direction or variations in meteorological conditions over time, providing only fixed, uniform impact ranges. As a result, it has limitations in selecting evacuation sites that consider seasonal weather characteristics and wind direction. To address this, this study additionally employed the ALOHA (Area Locations of Hazardous Atmospheres) program (version 5.4.7, NOAA and EPA, USA). ALOHA incorporates real-time meteorological conditions such as wind direction, wind speed, temperature, and humidity to simulate hazardous material dispersion and is widely used globally for chemical accident prevention and response planning [43].

2.4.1. Target Process

As shown in Figure 3, the styrene monomer process involves multiple stages of chemical reactions and purification steps to produce the final styrene monomer [44]. Each stage has a potential risk factor [45].

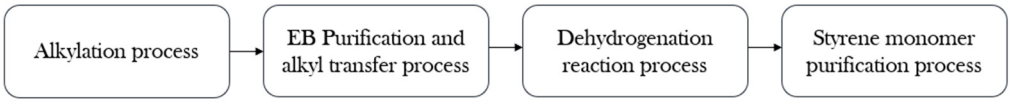


Figure 3. Process flow.

In the alkylation process that produces ethylbenzene (EB), ethylene reacts with benzene. EB purification and trans-alkylation processes then refine the produced ethylbenzene and recover the byproducts. Subsequently, the process advances to the dehydrogenation reaction stage, in which ethylbenzene is converted into a styrene monomer. Finally, in the SM purification process, unreacted materials, impurities, and byproducts are removed from the styrene monomer.

2.4.2. Meteorological Conditions

As shown in Table 3, the seasonal weather conditions for 10 years in the area where the target facility is located were analyzed and shown in Figure 4. The average temperature in spring (March to May) was 12.68 °C and the average humidity was 12.68 °C. 77.57%, the average southeasterly wind speed is 2.13 m/s. During summer (June to August), the average temperature is 26.66 °C, with an average humidity of 91.43% and an average wind speed of 2.17 m/s with southwesterly winds. During fall (September to November), the average temperature is 15.92 °C, with an average humidity of 85.43% and an average wind

speed of 1.86 m/s with northeasterly winds. During winter (December to February), the average temperature is 0.2 °C, with an average humidity of 79.67% and an average wind speed of 2.15 m/s with westerly winds [46].

Table 3. Seasonal weather conditions.

	Spring	Summer	Fall	Winter
Average temperature	11.37	23.8	14.97	2.23
Average humidity	66	79	76	72
Average wind speed	2.13	1.87	1.67	1.77
Maximum wind direction	135 SE	225 SW	50 NE	270 W

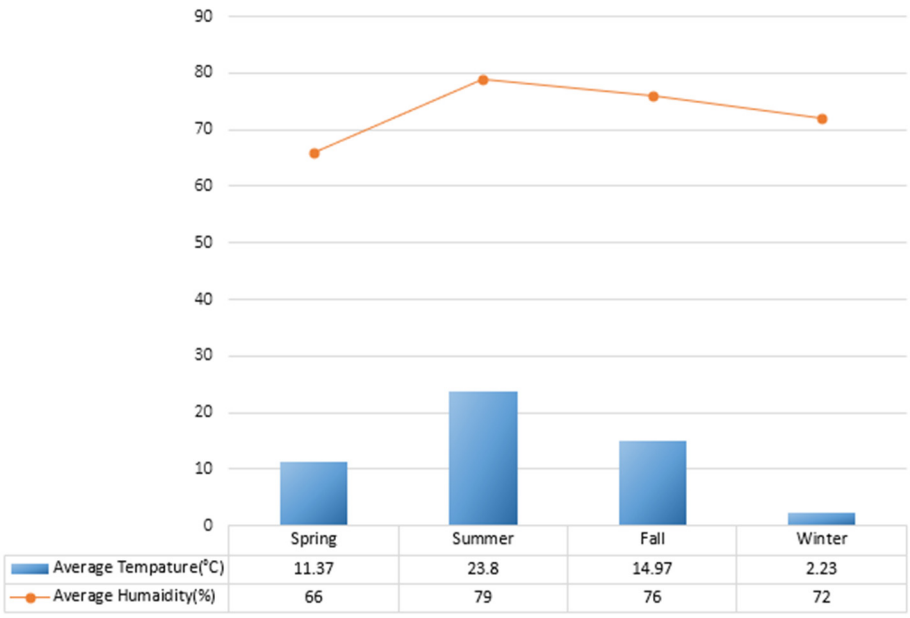


Figure 4. Meteorological conditions of the target area (2013–2023).

2.4.3. Accident Scenario

The accident scenario assumed a styrene monomer leak caused by an abnormal polymerization reaction of unknown origin inside a mixed residue oil storage tank at a styrene monomer plant [37–39]. This scenario was based on the conditions of the styrene monomer leak incident that occurred in 2019, with the meteorological conditions derived from an analysis of ten years of weather data for the region where the target facility was located. A summary of the accident scenarios is provided in Table 4.

Table 4. Input data.

	Accident Scenario
Wind speed	1.8 m/s at a height of 10 m above ground level
Atmospheric stability	F(stability)
Atmospheric temperature (humidity)	40 °C (50%)
Temperature of the leaked substance	146 °C
Wind direction	SE, SW, NE, W
Cloud cover	5
Leak point	0.5 m (emergency pressure release manhole diameter)
Elevation of the leak source	Assuming leakage from the ground surface
Tank diameter	5.8 m
Tank length	6.89 m
Tank volume	182 cu m
Tank mass	24.7 tons
Leakage opening	Circular opening

3. Results

3.1. Chemical Accident Evacuation Sites

An investigation of the chemical accident evacuation sites in Facility A revealed that, as shown in Figure 5, four chemical accident evacuation sites have been designated. However, all four evacuation sites are located in the southeast, with the minimum distance between the facility (potential accident site) and the evacuation sites being 6.4 km (Table 5). In the event of an accident involving the tank storing a large quantity of styrene monomer, there is a risk of exposure to hazardous chemicals for facility workers or nearby residents during winter when northwesterly winds prevail. Therefore, additional evacuation sites must be designated, considering the seasonal wind patterns.

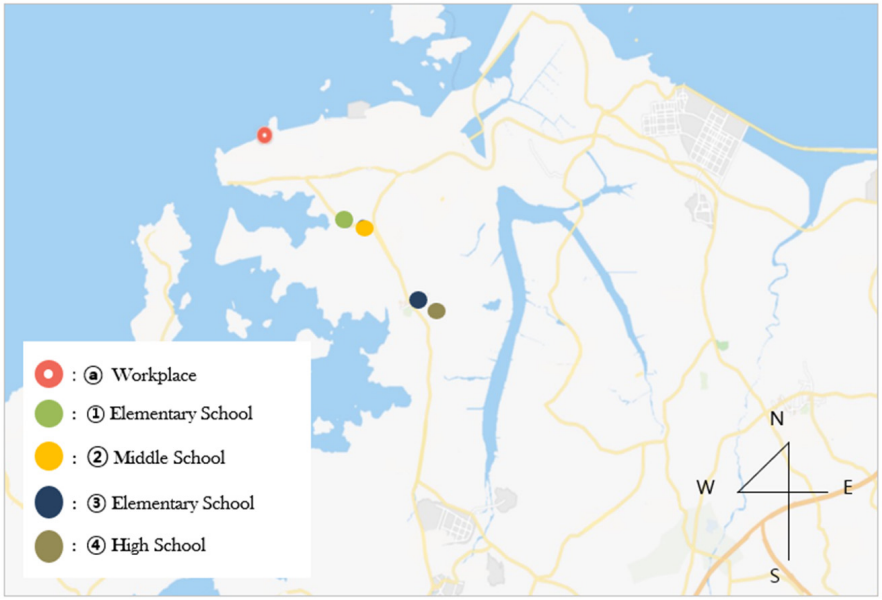


Figure 5. Chemical accident evacuation site at a facility.

Table 5. Locations of chemical accident evacuation sites.

	Location (Distance)
①	6.4 km
②	6.4 km
③	10 km
④	11 km

3.2. Damage Prediction Results

The analysis of the impact range of chemical accidents using KORA revealed an impact radius of 642.7 m and an off-site distance of 590.3 m. However, as shown in Figure 6, KORA only provides uniform ranges without considering wind direction.

ALOHA was used to overcome these limitations. The analysis results, as shown in Figure 7, indicated that during spring, chemical substances spread westward and northwestward under the influence of southeasterly winds. During summer, they spread northward and northwestward due to southwesterly winds. In autumn, they dispersed southward under the influence of northeasterly winds, and in winter, they spread eastward owing to westerly winds.

These results show that the direction of chemical dispersion varies based on the seasonal winds. The currently designated chemical accident evacuation sites located in the southeast are considered appropriate because of the geographic characteristics of the mountains and seas to the west and north, which restrict evacuation in these directions.



Figure 6. Impact Range in Case of an Accident.

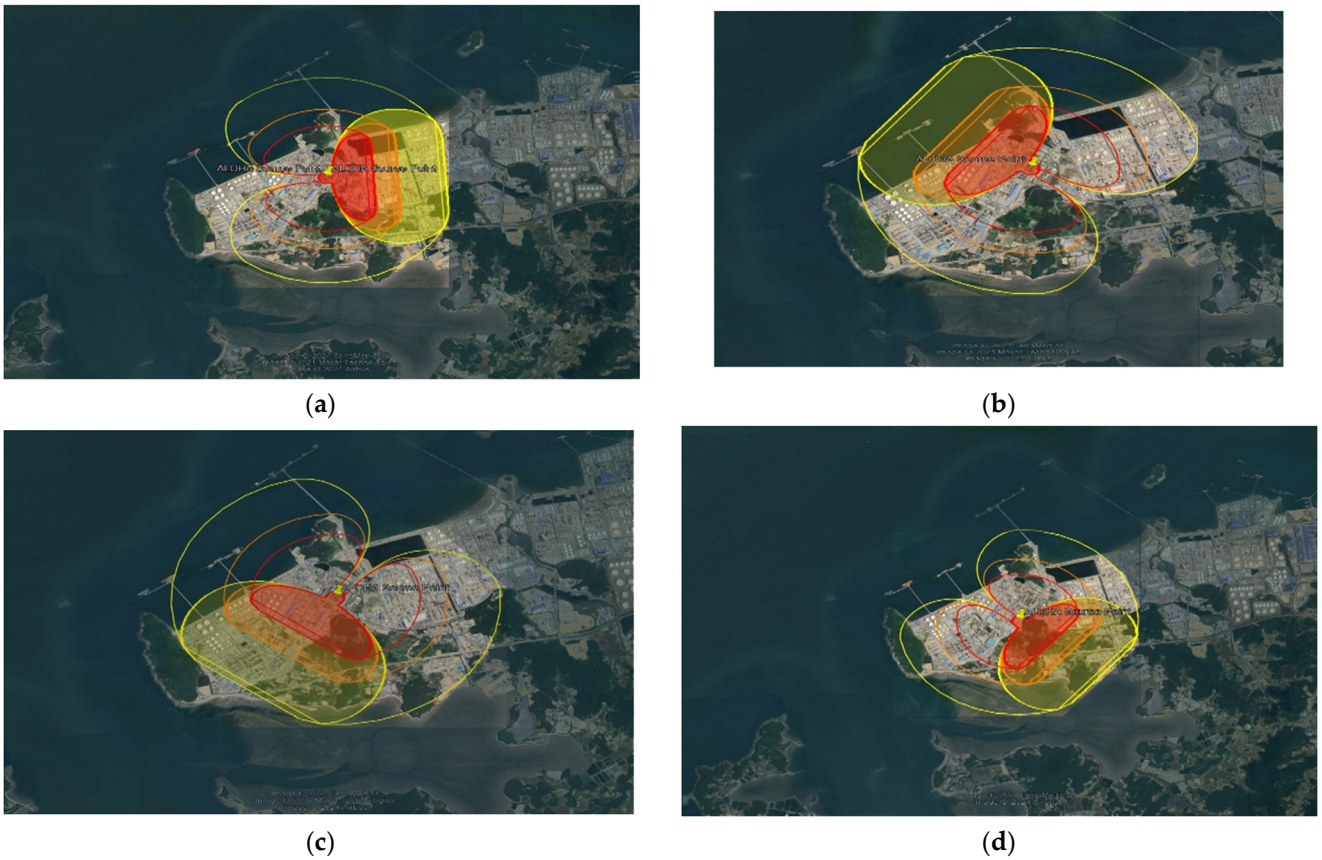


Figure 7. ALOHA analysis results. (**a**) Spring; (**b**) Summer; (**c**) Spring; (**d**) Summer.

However, evacuation toward the southwest and east is feasible, suggesting the potential for selecting additional evacuation sites. In addition, the minimum distance between the designated evacuation sites and the accident site was 6.4 km, which may pose challenges for on-foot evacuation by facility workers or nearby residents. Therefore, additional evacuation sites must be designated, considering the wind direction and feasibility of on-foot evacuation.

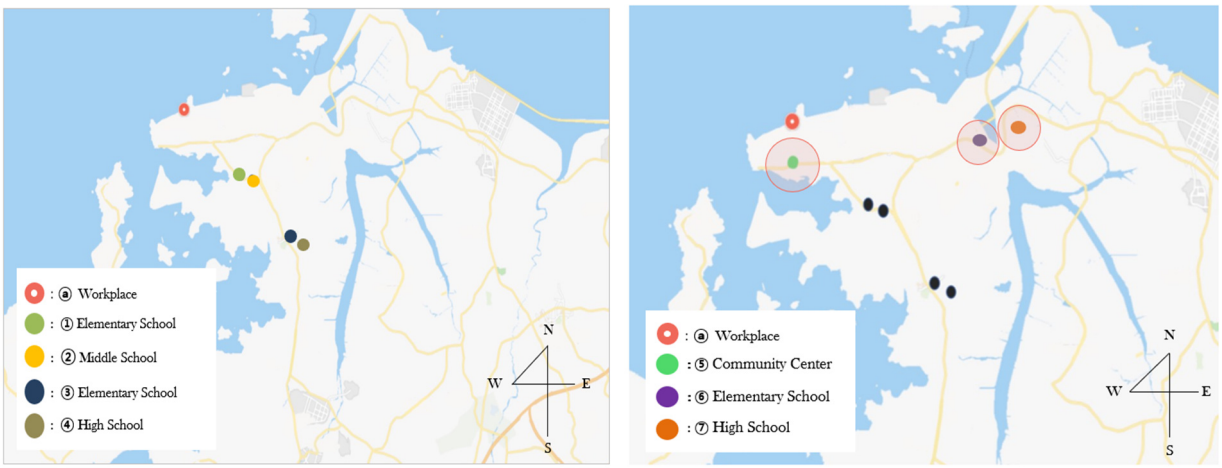
3.3. Improvement Measures

Wind direction and speed are the key factors in determining the direction and rate of hazardous material dispersal during a chemical accident. During summer, southwesterly winds were predominant at higher wind speeds, while northwesterly winds prevailed in the winter with lower wind speeds. These seasonal meteorological conditions significantly impact the dispersion range and affect areas of hazardous substances.

In this study, the correlation between meteorological conditions and chemical accidents was analyzed using the ALOHA software (version 5.4.7), confirming that affected areas vary by season. Based on these results, seasonal evacuation sites were proposed, taking into account meteorological factors such as wind direction and speed, as well as the number of evacuees traveling on foot. The comparison of current evacuation sites with additional proposed sites is summarized in Table 6, and their locations are shown in Figure 8.

Table 6. Locations and distances of chemical accident shelters.

Current Chemical Accident Evacuation Sites	Location (Distance)	Additional Evacuation Sites	Location (Distance)
① Elementary School	SE (6.4 km)	⑤ Community Center	S (1.4 km)
② Middle School	SE (6.4 km)	⑥ Elementary School	E (10 km)
③ Elementary School	SE (10 km)	⑦ Elementary School	E (13 km)
④ High School	SE (11 km)		



(**a**) (**b**)

Figure 8. Current and improved chemical accident evacuation sites. (**a**) Current evacuation sites. (**b**) Additional evacuation sites.

4. Conclusions

Evacuation sites play a crucial role in protecting people from the dispersion of hazardous chemicals and secondary damage. Since the dispersion path and range of hazardous substances vary depending on meteorological conditions such as wind direction and speed, evacuation sites must be carefully selected to ensure that evacuees are not exposed to these dispersion paths. Current regulations require the designation of at least two evacuation sites, taking wind direction into account, when selecting evacuation locations for chemical accidents. However, an analysis of evacuation sites reported by 10 facilities revealed that most sites were uniformly designated without adequately considering wind direction.

To address these issues, this study proposes evacuation site selection methods that consider seasonal wind direction and the feasibility of on-foot evacuation. An analysis of chemical accident evacuation sites at the target facility revealed that all currently des-

ignated evacuation sites are located in the southeast. This increases the risk of exposure to hazardous chemicals during the winter, when southwesterly winds are predominant. Using KORA to evaluate the impact range and ALOHA to analyze the impact range while considering wind direction, it was confirmed that the areas at risk of chemical dispersion vary by season. Additionally, the minimum distance from the accident site to the currently designated evacuation sites was found to be 6.4 km, presenting practical challenges for on-foot evacuation by workers or nearby residents.

In this study, additional evacuation sites were proposed, including one located 1.4 km away and others in the east and south, taking into account seasonal wind patterns. Currently, evacuation site selection guidelines suggest locating sites in the upwind direction of the accident site, considering immediate wind conditions. However, as proposed in this study, it is necessary to select evacuation sites that also account for seasonal wind patterns, ensuring the safety of evacuees under varying meteorological conditions. This highlights the importance of selecting evacuation sites based on seasonal wind direction and the feasibility of on-foot evacuation.

While this study considered seasonal wind patterns, it did not account for sudden and unpredictable weather changes. Furthermore, the proposed evacuation sites were based on the seasonal and geographical conditions specific to the target region, making it challenging to generalize the findings to facilities with unique geographical, meteorological, or operational conditions. However, for facilities with typical geographical and meteorological conditions, establishing evacuation sites that consider seasonal wind patterns, as proposed in this study, could facilitate prompt and safe evacuations during chemical accidents. Moreover, adopting the evacuation site selection methods proposed in this study is expected to effectively minimize secondary damage, even as areas of concern for chemical accident impacts shift due to seasonal wind pattern changes.

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