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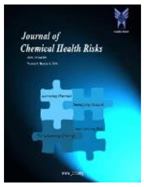

Shelter-in-Place as a Strategy for Mitigating Exposure to Toxic Gas Leaks in Malaysia: An In-depth Analysis

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ABSTRACT:

Malaysia's economic growth is significantly driven by its industrial sector, which includes high-risk industries prone to chemical accidents and toxic gas emissions. The shelter-in-place (SIP) strategy, which advises residents to stay indoors during chemical releases, has become a critical response measure. However, its effectiveness in Malaysia varies due to factors like building integrity, population density, chemical usage, and weather conditions that influence gas dispersion. This study assesses SIP's effectiveness in Malaysia by examining various contextual factors and highlighting the role of public awareness and preparedness. It uses case studies and best practices globally to propose improvements in building codes, construction practices, and public education to optimize SIP's effectiveness. This comprehensive analysis aims to enhance Malaysia's emergency response strategies, ensuring better community protection against chemical hazards. The study critically explores the strengths and limitations of SIP and provides recommendations for enhancing public safety protocols, thus contributing to the broader discourse on emergency preparedness in the face of industrial risks.

1. Introduction

Malaysia's economic prosperity is significantly bolstered by its dynamic industrial sector, which encompasses manufacturing, petrochemicals, and other high-risk industries [1–4]. This industrialization, while a key driver of economic development and job creation, also brings with it an increased risk of chemical accidents and toxic gas emissions [5,6]. The history of industrial accidents in Malaysia, including notable incidents of toxic gas releases [7,8], underscores the urgent need for effective public protection strategies to safeguard communities against potential chemical hazards.

Shelter-in-place (SIP) has emerged as a critical tactic in the arsenal of emergency response measures for such scenarios. SIP involves residents and individuals in the vicinity of a chemical release staying indoors, closing all windows and doors, and sealing any gaps where contaminants might enter, to minimize exposure to toxic substances. This measure, when effectively implemented, can significantly reduce the health risks associated with accidental releases of hazardous chemicals into the atmosphere [9,10].

However, the effectiveness of SIP is not uniform and can be influenced by a multitude of contextual factors specific to Malaysia. These include the architectural integrity and design of buildings, the density of population areas prone to such risks, the nature and volume of chemicals used in local industries, and the prevailing weather conditions that can affect the dispersion of toxic gases [11–13]. Moreover, the level of

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public awareness and preparedness to respond to emergency instructions plays a crucial role in the success of SIP measures [14,15,10].

This study aims to critically assess the application and effectiveness of SIP in the Malaysian context, exploring how these various factors contribute to or detract from its success as a public protection strategy. Through an examination of case studies, literature, and best practices from around the globe, this paper seeks to identify the strengths and limitations of SIP in Malaysia. It will highlight key areas where improvements can be made, from enhancing building codes and construction practices to improving public education and communication during emergencies. By understanding the intricacies of SIP's application in Malaysia, this study will offer recommendations aimed at optimizing its effectiveness, ensuring that communities are better protected in the event of chemical emergencies.

In doing so, the study will address several critical questions: How have past toxic gas incidents been managed in Malaysia, and what lessons can be learned? What are the specific challenges to implementing SIP in Malaysia's diverse urban and rural settings? And, most importantly, how can Malaysia enhance its SIP protocols to better protect its citizens from the dangers of toxic gas exposures? Through a comprehensive exploration of these questions, this paper aims to contribute valuable insights to the ongoing discourse on emergency preparedness and public safety in the face of chemical hazards in Malaysia.

2. Building Integrity and Toxic Gas Leak Dynamics

The premise of SIP as an effective emergency response hinges significantly on the structural integrity of buildings within which individuals seek refuge [16,17]. In Malaysia, the diversity in building construction materials and practices raises important considerations for SIP's viability [18–22]. Research indicates that a significant number of Malaysian buildings, especially residential ones, are constructed using concrete or brick materials [23]. Although these materials are readily accessible and available, their effectiveness in creating airtight seals to prevent the infiltration of toxic gases due to the building designs remains uncertain. The porosity and seal integrity of windows, doors, and ventilation systems in such buildings can vary widely, impacting their ability to serve as effective barriers against hazardous substances [24,25,12].

The challenge is further compounded by the dynamic nature of toxic gas releases. The physical and chemical properties of the released gas—such as its density relative to air, solubility, and reactivity—significantly influence how the gas behaves once released into the environment [26,27]. Gases that are heavier than air, for example, tend to accumulate at ground level and can seep into buildings more readily, especially in areas with poor ventilation or inadequate sealing [28].

Environmental conditions at the time of the leak also play a pivotal role. Wind speed and direction can affect gas dispersion patterns, while temperature and humidity levels can influence the gas's concentration and persistence in the air [29–31]. Leaks occurring under stagnant air conditions, where there is little to no wind to disperse the gas, pose a heightened risk as the concentrated gas cloud can envelop buildings, challenging the effectiveness of SIP measures [32].

Moreover, the interaction between the built environment and gas dynamics necessitates a nuanced understanding of risk assessment and mitigation strategies. For instance, buildings designed with advanced ventilation systems and air filtration technologies offer a higher level of protection by actively reducing indoor contaminant levels [33]. However, the widespread implementation of such technologies in Malaysia is limited by cost and practicality considerations, especially in older buildings or economically disadvantaged areas [34,35].

Addressing these challenges requires a multifaceted approach. Enhancing building codes to prioritize airtightness and incorporating passive and active ventilation strategies can significantly improve SIP outcomes [36,37]. Equally important is the development of comprehensive risk assessment tools that consider both the specific characteristics of potential toxic gases and the local building practices. Such tools can guide emergency planners and responders in making informed decisions about when and where SIP is most likely to be effective [13,38,12,39].

Furthermore, public education campaigns tailored to the Malaysian context can empower residents with the knowledge to improve the seal integrity of their homes and understand the limitations of SIP in different scenarios [40,41]. This includes practical advice on emergency sealing techniques, the use of air purifiers, and the importance of staying informed about local industrial activities and the types of chemicals in use [42–44].

In brief, the effectiveness of SIP in Malaysia is intricately linked to the interplay between building integrity and the dynamics of toxic gas leaks. By addressing these critical factors through improved construction practices, targeted public education, and advanced risk assessment methodologies, Malaysia can enhance its resilience to chemical emergencies and better protect its citizens from the dangers of toxic gas exposure.

3. Case Studies and Literature Review

A thorough examination of past toxic gas incidents in Malaysia provides invaluable insights into the practical application and efficacy of SIP strategies. By dissecting documented cases and analyzing relevant academic studies, this section evaluates the real-world outcomes of SIP, identifying successful applications and areas for improvement. Additionally, a comparative analysis with countries possessing similar industrial profiles and emergency management frameworks offers a broader perspective on SIP's global best practices [40].

3.1 Malaysian Case Studies:

i. Petrochemical Plant Leak (2016): An unfortunate incident occurred at the Petronas Chemicals Fertiliser Sabah Sdn. Bhd. facility. During maintenance work, an ammonia leak resulted in two fatalities and affected three other workers [45]. Despite the severity of the situation, no SIP advisory was issued. However, in the event of such incidents, the immediate implementation of SIP can significantly reduce the risk of exposure to hazardous substances, thereby safeguarding the health and safety of workers and the surrounding community [40].
ii. Pasir Gudang Industrial Chemical Spill (2019): This incident involved the release of hazardous gases from illegal chemical waste dumping, affecting over 5,000 individuals with symptoms of poisoning and necessitating mass evacuations [46,8,47,48]. No SIP advisory was issued during this crisis, which highlights a missed opportunity for reducing exposure and underscores the need for rapid dissemination of information and public compliance [49]. Analysis of this case reveals challenges in public awareness and preparedness, with the absence of SIP instructions potentially contributing to the incident's health impact [48].

3.2 International Comparative Analysis:

Drawing lessons from international experiences enriches the understanding of SIP's application. For instance:

i. United States - Richmond, California Refinery Fire (2012): The response to this refinery fire, which emitted a large plume of toxic smoke, included SIP orders for nearby residents. The incident emphasized the significance of community preparedness and the effectiveness of early warning systems [50,51]. Malaysia can learn from Richmond's community engagement practices and the implementation of advanced alert systems to enhance SIP responsiveness.
ii. China - Tianjin Chemical Explosion (2015): The catastrophic explosion in Tianjin resulted in significant chemical exposure. The emergency response highlighted issues similar to those faced in Malaysia, such as the need for timely public information and the challenges of managing large-scale evacuations [52]. Insights from Tianjin suggest the importance of integrating SIP strategies with evacuation plans, especially for incidents involving widespread contamination [53,54].
iii. United States - Altivia Plant Toxic Gas Leak (2023): A toxic gas leak at Altivia Chemicals' La Porte, Texas plant resulted in eight individuals being hospitalized. In response to the emergency, the city issued a SIP order affecting several neighbouring industrial facilities. This measure aimed to minimize exposure to the hazardous gas among workers and nearby residents. The leak was traced back to a ruptured pressure release device, prompting the shutdown of all operations at the La Porte site to ensure safety. The SIP order was effectively managed and lifted approximately one hour after its implementation, demonstrating the importance of timely and coordinated emergency response measures in mitigating the impact of toxic gas releases [42,55,56].

3.3 Lessons Learned and Benchmarks:

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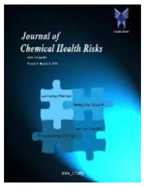

The review of case studies within Malaysia and comparisons with international incidents reveal several key lessons:

i. Importance of Public Awareness and Education: Consistent public education on SIP procedures and emergency preparedness is critical. Malaysia can enhance its SIP outcomes by adopting ongoing education campaigns and leveraging media to disseminate information effectively [57,58].
ii. Need for Robust Early Warning Systems: The implementation of advanced early warning and real-time monitoring systems can significantly improve SIP effectiveness by ensuring timely advisories are issued [59–61].
iii. Integration with Evacuation Plans: SIP should not be viewed in isolation but as part of a holistic emergency response strategy that includes evacuation options for scenarios where SIP may not be sufficient [18,10,62,63].
iv. Building and Infrastructure Readiness: Improving the seal integrity of buildings and ensuring that critical infrastructure is equipped for SIP can mitigate the risks associated with toxic gas exposure [40,64,65,10].

By examining these case studies and incorporating international best practices, Malaysia can refine its SIP strategies to better protect its citizens from the dangers of toxic gas leaks. This review underscores the necessity of a multifaceted approach to emergency preparedness, combining public education, infrastructure improvements, and robust early warning systems to enhance the overall effectiveness of SIP measures.

4. Strengths and Limitations of Shelter-in-Place (SIP)

4.1 Strengths of SIP

i. Rapid Deployment: One of the most significant strengths of SIP is its ability to be quickly implemented. In the event of a toxic gas release, authorities can immediately advise the public to shelter in place, a directive that can be rapidly disseminated through various communication channels such as social media, text alerts, and sirens. This immediacy can be crucial in minimizing exposure to hazardous substances [12,38].
ii. Low Resource Dependency: SIP requires relatively few resources compared to large-scale evacuations. It leverages existing infrastructure (i.e., people's homes and buildings) as protective shelters, avoiding the logistical complexities and resources needed for transporting, housing, and supporting displaced populations [66,67,12,68].
iii. Minimization of Exposure: By staying indoors, individuals can significantly reduce their exposure to toxic gases, especially when buildings are adequately sealed. This is particularly effective in the initial hours following a release when the concentration of toxic substances in the air outside may be at its highest [69,70,10].

4.2 Limitations of SIP

i. Prolonged Indoor Stays: SIP can necessitate extended periods indoors, which may not always be feasible or safe, depending on the building's suitability and the duration of the hazard. Extended stays can lead to challenges in accessing fresh air, food, water, and medical supplies, particularly for individuals with health conditions that require regular care or medication [25,71,10].
ii. Psychological Impacts: The stress and anxiety associated with SIP situations, especially when prolonged and without clear communication, can have significant psychological impacts on individuals. This includes feelings of isolation, fear, and uncertainty, which can be exacerbated in individuals with pre-existing mental health conditions [72–75].
iii. Communication Failures: Effective SIP implementation heavily relies on timely and clear communication from authorities. The risk of communication failures—due to overloaded systems, power outages, or misinformation—can undermine SIP directives, leading to confusion and non-compliance among the public [76–78].
iv. Vulnerable Populations: Certain groups face unique challenges with SIP. Individuals with disabilities may find it difficult to ensure their shelter is adequately sealed or may require specific medical equipment that SIP conditions can disrupt [79,80].
v. Variability in Building Integrity: The effectiveness of SIP is highly dependent on the structural integrity and airtightness of buildings. In areas where buildings are not designed to minimize air infiltration, the protection SIP offers can be significantly reduced.

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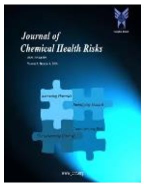

This variability raises concerns about the equitable protection of all community members, regardless of their living conditions [36,18,25,10].

4.3 Addressing the Limitations

To enhance the efficacy of SIP, it is crucial to address these limitations through targeted strategies:

i. Improving Public Communication: Develop robust communication plans that utilize multiple platforms to ensure reliable, clear, and consistent messaging throughout the duration of a SIP advisory [81,82].
ii. Enhancing Building Readiness: Advocate for building codes that improve the sealability and ventilation of structures, particularly in new constructions and high-risk areas [83,84].
iii. Supporting Vulnerable Groups: Create specific protocols and support systems for vulnerable populations, ensuring they have the necessary resources and assistance to effectively SIP [85,86].
iv. Psychological Support Services: Incorporate mental health support into SIP planning, offering access to counselling services and guidance on managing stress and anxiety during prolonged indoor stays [72,86,87].

By critically examining the strengths and limitations of SIP and implementing strategies to address its challenges, emergency management authorities can optimize this response measure to protect public health and safety during toxic gas releases more effectively.

5. Recommendations for Enhancement

i. Public Awareness Initiatives

- Targeted Information Campaigns [88,89]: Develop and deploy targeted public information campaigns that cater to diverse segments of the population, including schools, businesses, and residential communities. Utilize a variety of media platforms — social media, television, radio, and print — to disseminate information on SIP procedures, the importance of emergency preparedness, and the limitations of SIP in certain situations.
- Community Engagement and Training [90,91]: Organize community engagement sessions and training workshops to educate the public on practical SIP measures, such as how to effectively seal a room and the essentials of creating an emergency preparedness kit. Collaborate with local community leaders and organizations to facilitate these sessions, ensuring wide-reaching impact.

ii. Building Regulations Revision

- Enhancement of Building Codes [92]: Work with relevant regulatory bodies to review and update building codes, focusing on improving the airtightness of structures and the compatibility of ventilation systems with SIP requirements. Encourage the incorporation of passive ventilation systems that can be manually controlled to minimize air infiltration during a SIP advisory [93,94].
- Incentives for Retrofitting [95,96]: Introduce incentives for homeowners and businesses to retrofit existing buildings to meet enhanced SIP-related standards. This could include financial subsidies, tax rebates, or assistance programs aimed at making buildings more resistant to toxic gas infiltration.

iii. Emergency Response Optimization

- Comprehensive Emergency Plans [97,13,12]: Develop and regularly update comprehensive emergency response plans that include specific SIP protocols. These plans should detail efficient communication strategies, including the use of emergency alert systems to notify the public of SIP advisories, clear evacuation protocols for when SIP is not viable, and guidelines to support at-risk populations.
- Interagency Coordination [98,99]: Strengthen interagency coordination among emergency services, health departments, environmental agencies, and community organizations to ensure a unified and effective response during toxic gas emergencies. Conduct regular joint exercises to test and refine emergency plans and SIP protocols.

iv. Technological Advancements in Monitoring

- Real-Time Air Quality Monitoring [100–102]: Invest in the expansion and upgrade of air quality monitoring networks to provide real-time data on toxic gas concentrations. Ensure that monitoring stations are strategically located near industrial areas and densely populated communities for optimal coverage and accuracy.
- Advanced Gas Dispersion Modelling [11,29,103]: Utilize advanced gas dispersion models to predict the movement and concentration of toxic gases following

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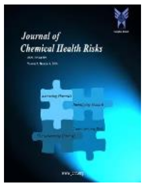

a release. Integrate these models with emergency management systems to inform decision-making processes, including the issuance of SIP advisories and the activation of evacuation plans when necessary.

- Public Access to Information [104,105]: Develop a platform or mobile application that provides the public with access to real-time air quality data and emergency advisories. This tool can empower individuals to make informed decisions about their safety during toxic gas incidents.

6. Conclusion

Shelter-in-place (SIP) has emerged as a crucial tactic in safeguarding the Malaysian populace from the dangers posed by accidental releases of toxic gases. Its role in the nation's emergency response framework is undeniable, offering a rapid and resource-efficient means to mitigate exposure during chemical emergencies. However, the effectiveness of SIP is not a given; it is contingent upon a myriad of factors ranging from the structural integrity of buildings to the speed and clarity of communication during crises. The study has underscored that while SIP holds significant promise, its current application reveals gaps that must be addressed to fully realize its potential.

The journey towards refining SIP in Malaysia involves a comprehensive approach that touches on various aspects of emergency preparedness and public safety. Critical to this endeavour is the need for ongoing evaluation and refinement of SIP strategies to ensure they remain responsive to evolving risks and technological advancements. Addressing the current shortcomings identified in this study—such as enhancing building airtightness, improving public awareness and compliance, optimizing emergency communication, and leveraging technological advancements for real-time monitoring—constitutes the immediate steps towards fortifying the SIP protocol.

Moreover, the complexity of implementing effective SIP measures calls for a collaborative effort that transcends individual stakeholders. It necessitates a partnership between government agencies, the private sector, non-governmental organizations, and the community at large. By fostering a culture of preparedness and resilience, Malaysia can cultivate a more informed and responsive populace capable of acting decisively during toxic gas emergencies.

Customizing emergency protocols to align with Malaysia's unique demographic, geographic, and infrastructural context is paramount. This customization involves not just a technical recalibration of existing protocols but also a cultural shift towards a more proactive and preventive approach to disaster management. Empowering communities with the knowledge and tools to effectively implement SIP, coupled with infrastructure that supports such measures, will be key to minimizing the public health impacts of toxic gas releases.

As Malaysia continues to advance its industrial capabilities, the potential risks associated with toxic gas leaks cannot be overlooked. Therefore, enhancing the SIP strategy is not merely an exercise in emergency response optimization but a necessary step towards safeguarding the nation's health, environment, and future prosperity. Through committed action, ongoing research, and adaptive policy-making, SIP can evolve into a more robust and effective element of Malaysia's emergency response framework, offering a beacon of safety and resilience in the face of chemical hazards.

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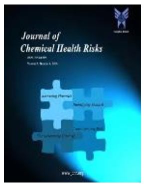

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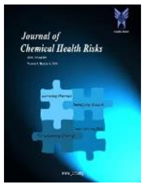

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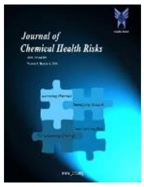

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