

APPLICATION OF THE HIERARCHY OF CONTROLS FOR RISK REDUCTION OF DUST EXPLOSIONS IN A TAPIOCA STARCH FACTORY IN UBON RATCHATHANI, THAILAND

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Abstract

Dust explosions pose a significant risk across various industries worldwide, leading to injuries, fatalities, property damage, and environmental consequences. Accurate risk assessment techniques are essential for identifying hazards and implementing preventive measures to mitigate the risk of dust explosions. This research and development study aims to evaluate dust explosion risks using the Risk Assessment Matrix (RAM) to identify and prioritize hazards, and controls were applied using the Hierarchy of Controls which prioritizes risk reduction strategies from elimination to personal protective equipment. Data were collected from a tapioca starch factory in Ubon Ratchathani, Thailand, between June 2023 and March 2024. The RAM assessment indicated a very high risk (level 4) of dust explosions. Key contributing factors included the presence of combustible dust, oxygen, confinement, dust dispersion, and ignition sources. Notably, the primary ignition risks were associated with human error (violations of safety procedures) and mechanical failure (bolts, nuts, and bearing malfunction). Risk mitigation measures were developed and implemented based on the Hierarchy of Controls. Following the intervention, the overall risk was reduced by 52.71%. Elimination and engineering controls were more effective in preventing dust explosions than administrative controls. These findings suggest that integrating RAM with the Hierarchy of Controls provides a practical and reliable approach to reducing explosion risks and enhancing safety in dust prone industrial environments.

Keywords: Dust Explosion, Hierarchy of Controls, Risk Assessment Matrix

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Introduction

Dust explosions frequently occur in industrial processes, resulting in severe injuries, fatalities, and extensive property damage

These explosions can also impact surrounding areas, thereby amplifying their destructive consequences (Prasad *et al.*, 2021). Globally, more than 2,000 dust explosion incidents have been reported, with the highest prevalence observed in China (38.10%), followed by the United States (18.7%) and Canada (6.4%) (Yuan *et al.*, 2015b). Between 1998 and 2021, China alone experienced 67 such incidents, resulting in 547 fatalities and 600 injuries (Guan *et al.*, 2023).

Between 2006 and 2020, 211 dust explosions in the United States resulted in 70 fatalities and 452 injuries (Pang *et al.*, 2023). Most of these incidents are attributed to heat transfer (Amyotte & Eckhoff, 2010). The National Fire Protection Association (NFPA) defines combustible dust as particulate matter with a diameter of less than 420 μm , composed of natural organic materials, synthetic organic compounds, coal, peat, or metals (NFPA 664, 2018). Dust explosions require five essential components, often referred to as the 'dust explosion pentagon': combustible dust, oxygen, confinement within enclosed spaces or equipment, ignition sources, and the dispersion of a dust cloud (Wei *et al.*, 2020). Ignition sources are the primary cause of dust explosions and include various triggers such as flame and direct heat (22%), hot work (20%), electric sparks (12%), static electricity (10%), impact sparks (9%), self-heating and smoldering (8%), friction sparks (7%), hot surfaces (6%), and other factors (6%) (Yuan *et al.*, 2015b).

A notable example is the 2008 explosion at the Imperial Sugar factory in Port Wentworth, Georgia, caused by friction-induced ignition sources that generated flames and direct heat, with a 6.50% probability of spark generation (Abuswer *et al.*, 2013). In China, coal dust explosions are often linked to cable short circuits and poor ventilation systems, exacerbated by delays in implementing dust explosion prevention measures (Shi *et al.*, 2018). According to the NFPA, dust particles capable of causing explosions must have a maximum diameter of less than 420 μm , a minimum combustible concentration of 125 g/m^3 , a maximum explosion pressure (P_{max}) of 9.4 bar, and a maximum rate of pressure rise (K_{st}) of 62 $\text{bar}\cdot\text{m}/\text{s}$ (Wei *et al.*, 2020; Lu *et al.*, 2023).

Considering the significant risks posed by dust explosions across various industries, numerous effective risk assessment tools have been developed

to address this critical issue. These tools include Failure Mode and Effects Criticality Analysis (FMECA), Failure Mode and Effects Analysis (FMEA), the Hierarchy of Control, and Fault Tree Analysis (FTA) (Abuswer *et al.*, 2013; Shi *et al.*, 2018; Mahmood *et al.*, 2022; Spasenic *et al.*, 2022). Furthermore, the Analytic Hierarchy Process (AHP) has been integrated with other risk assessment methods, such as FTA, Job Safety Analysis (JSA), Fuzzy Comprehensive Evaluation (FCE), and risk matrices, to enhance accuracy in identifying process errors, ranking risks, and prioritizing corrective actions (Pang *et al.*, 2023; Ok *et al.*, 2022; He *et al.*, 2023).

Due to the profound consequences of dust explosions, safety precautions have been implemented to eliminate explosion factors and minimize potential damage (Eckhoff, 2003). Effective prevention requires a combination of approaches, including a hierarchical structure integrated with engineered controls—both passive and active (Amyotte *et al.*, 2009). To support these measures, the National Institute for Occupational Safety and Health (NIOSH) has issued guidelines to help businesses ensure worker safety, health, and well-being (McLellan *et al.*, 2017).

Research on dust explosions highlights the extensive loss of life and property, underscoring the importance of robust control measures to mitigate these risks (Zhang *et al.*, 2017). Diverse risk assessment tools have been shown to effectively identify explosion risks and provide accurate, context-specific insights.

The Hierarchy of Controls is a particularly effective accident prevention framework, comprising elimination, substitution, engineering controls, administrative measures, and personal protective equipment (PPE) (Hudson *et al.*, 2021).

Dust explosion statistics highlight the significant impact on human life, health, and property, causing immeasurable damage. While previous studies have focused on risk assessments in the tapioca starch production process, no such assessment has been conducted for the tapioca chip storage process, which is the initial step in tapioca starch production. Furthermore, preventive measures against explosions in this phase have not been thoroughly examined. Therefore, this study aims to assess the risk of dust explosions in the tapioca chip storage process and preventive measures by applying the Hierarchy of Controls in the tapioca starch factory in Ubon Ratchathani, Thailand.

Materials and Methods

Study design and setting

This research and development study was conducted from June 2023 to March 2024. The study area was specifically chosen based on available data on dust explosion incidents between 2020 and 2023 in the tapioca chip storage process, as well as the willingness of the facility to cooperate throughout the research period. A case study was conducted at a tapioca starch factory in Ubon Ratchathani, Thailand.

Risk identification

This study focuses on the primary risks associated with dust explosions, particularly those caused by ignition sources and dust dispersion. Three essential components of the tapioca chip storage process are involved: bucket elevators, motor sets, and tripper car conveyors (Figures 1-2).

1. The bucket elevator (double leg) is a vertical conveying system comprising several components: 1) a bucket that lifts raw material from the bottom to the top and transfers it to the tripper car conveyor, 2) a rubber belt that drives the roller and conveyor belt, enabling the transportation of tapioca chips, and 3) a nut that connects the bucket to the rubber belt, ensuring secure operation.

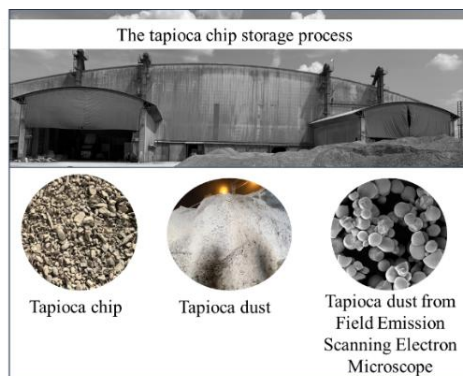


Figure 1. The tapioca chip storage

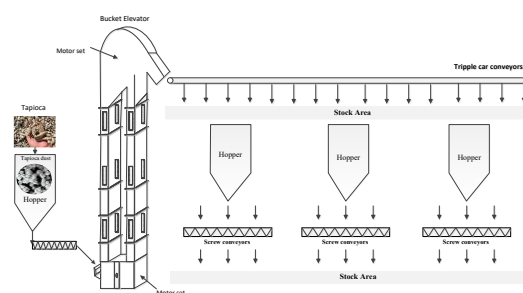


Figure 2. The tapioca chip storage process

2. The motor set generates power to drive the conveyor system and includes: 1) the motor, which reduces speed via the motor gear; 2) the bearing, which supports the weight and reduces friction to enable efficient shaft rotation; and 3) the set screw, which secures the conveyor system components.

3. The tripper car conveyor is a conveying device comprising the following components: 1) a motor drive that transmits power to the conveyor, 2) a roller that supports the belt, 3) a belt that transports material from one point to another, 4) pulleys that support and drive the belt while controlling its tension, and 5) a gear motor that drives or stops the conveyor belt.

We established the Dust Explosion Prevention and Mitigation Committee (DEPM), consisting of 16 members selected from four groups within the factory: management, production staff, engineers, and safety officers. The members were chosen based on relevant experience, ranging from 5 to over 10 years, in factory operations, dust-prone processes, explosion control systems, and occupational safety. This multidisciplinary expertise enables effective risk identification and mitigation following industrial safety standards. Each group comprises four members, and the DEPM's roles and responsibilities are outlined as follows:

1. The committee conducted a comprehensive identification of dust explosion risks by applying the dust explosion pentagon framework. The analysis focused particularly on two high-risk factors: dust dispersion and ignition sources associated with the tapioca chip storage and transfer processes. Risk identification was conducted through onsite walkthrough surveys, process observations, incident records review, and interviews with workers and supervisors. This process was conducted twice, before and after the Hierarchy of Controls (HC) intervention, in June 2023 and March 2024.

2. The potential hazards identified were systematically analyzed using a qualitative risk matrix method. Likelihood and severity ratings were assigned through consensus among DEPM members during formal committee meetings. Two meetings were held, one before the intervention (June 2023) and another following the intervention (March 2024). During these sessions, hazard scenarios were discussed in detail, and supporting data from incident logs and dust sampling reports were examined.

3. Risk Evaluation: The committee used the same risk matrix to evaluate and prioritize the identified risks. This process involved ranking each hazard according to its overall risk score and

determining whether it required immediate or long-term control measures. Evaluation results were recorded using standardized risk assessment forms. This evaluation was conducted in June 2023 and March 2024, before and after the HC intervention, respectively.

4. Risk Treatment: To mitigate the prioritized risks, the DEPM developed action plans based on the Hierarchy of Controls, following the preferred sequence: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE). Specific interventions included installing dust extraction systems, redesigning storage layouts, and revising maintenance schedules. Implementation was carried out over eight months from July 2023 to February 2024 and monitored for fidelity and practicality.

5. The effectiveness of the implemented measures was assessed using a Protection Factor (PF), calculated as the ratio of the initial risk rating (before intervention) to the residual risk rating (after intervention). Validation of the changes in risk profiles was performed through site audits, worker feedback, and follow-up inspections conducted in June 2023 and March 2024.

All committee proceedings, including meeting minutes, action plans, and risk assessment results, were formally documented and reviewed by the factory's executive management team. This process ensured accountability, traceability, and the potential for replication in standard (Figure 3).

Risk matrix method

A risk assessment matrix, also known as a probability and severity or likelihood and impact matrix, is used to evaluate exposure severity and probability. Severity is graded on a scale from 1 to 4, with 1 representing insignificant severity, such as no injuries or diseases, minimal system disruptions,

or chemical releases that do not require reporting. A severity rating of 2 indicates the need for first aid or minor medical treatment, non-serious equipment or facility damage, or a minor chemical release that requires routine cleanup without reporting (negligible). A severity rating of 3 refers to situations requiring medical treatment or restricted work, minor subsystem loss or damage, or chemical releases that trigger external reporting requirements (marginal). Finally, a severity rating of 4 indicates disabling injury or illness, significant property damage and business downtime, or chemical releases with temporary environmental or public health impacts. Probability is assessed on a scale from 1 to 5, with 1 indicating unlikely, 2 representing rare, 3 corresponding to occasional, 4 denoting likely, and 5 indicating often. The risk rating matrix is utilized to identify the most commonly reported hazards and determine high-risk factors. Based on these assessments, risks are evaluated accordingly, and the findings are presented in a color-coded risk-rating matrix (Figure 4) (Kannan & Naveen, 2024; Popov *et al.*, 2016).

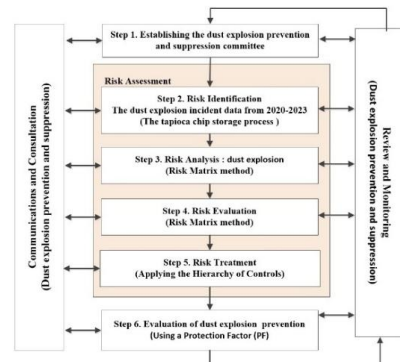


Figure 3. Shows DEPM's roles and responsibilities

Risk matrix		Probability				
		1	2	3	4	5
Severity	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5

Incident or severity descriptions		
5	Catastrophic	One or more fatalities, total system loss, chemical release with lasting environmental or public health impact
4	Critical	Disabling injury or illness, major property damage and business downtime, chemical release with temporary environmental or public health impact
3	Marginal	Medical treatment or restricted work, minor subsystem loss or damage, chemical release triggering external
2	Negligible	First aid or minor medical treatment or minor medical treatment only, non-serious equipment or facility damage, chemical release requiring routine cleanup without reporting
1	Insignificant	Inconsequential with respect to injuries or illnesses, system loss or downtime, or environmental chemical release

Risk matrix		
Scoring	Risk level	Descriptions
≥ 15	4	Very high risk
9-14	3	High risk
4-8	2	Moderate risk
< 4	1	Low risk

Incident or probability descriptions		
5	Frequent	Likely to occur repeatedly
4	Likely	Probably will occur several times
3	Occasional	Could occur intermittently
2	Seldom	Could occur, but hardly ever
1	Unlikely	Improbable, may assume incident or exposure will not occur

Figure 4. Shows risk assessment matrix and risk rating

Notes: Scores of 1-3 indicate low risk (maintain measures); 4-8, moderate risk (review measures); 9-14, high risk (improve measures); ≥15, very high risk (consider halting activity)

Risk treatment

Risk treatment, guided by the Hierarchy of Controls (HC), is a highly effective approach for preventing and managing dust explosions. This method was applied following a comprehensive risk assessment and the development of a risk rating matrix. The HC framework utilizes these assessment results to establish a tailored dust explosion prevention model for the tapioca storage process. The hierarchy includes: 1) Elimination: Removing the hazard entirely; 2) Substitution: Replacing the hazard with a less harmful alternative; 3) Engineering Controls: Implementing design and engineering solutions to separate individuals from the hazard; 4) Administrative Controls: Modifying work practices through training and policies; and 5) Personal Protective Equipment (PPE): Equipping individuals with protective gear and clothing (Hudson *et al.*, 2021).

The effectiveness of dust explosion prevention strategies is evaluated using a protection factor, which allows for the selection and integration of existing and potential measures into the risk assessment. To reflect the level of protection provided by each control measure, the risk estimate is updated accordingly. The risk reduction effectiveness is calculated using the formula: Risk = Severity $\times$ (Probability $\times$ Protection Factor).

Evaluation of dust explosion prevention

The protection factor multipliers for various control measures are as follows: elimination = 0.10, substitution = 0.40, engineering (multiple measures) = 0.60, engineering (single measure) = 0.70, warning systems = 0.80, administrative controls = 0.90, PPE = 0.95, and no control = 1 (Popov *et al.*, 2016).

Ethical Issues/Statement

This research was approved by the Mahasarakham University Ethics Committee for Human Subjects (approval number 121-031/2023). All participants provided written informed consent prior to their enrollment in the study.

Results and Discussion

Risk identification and risk analysis

The dust explosion risk assessment, using the risk matrix, categorized the highest risk as level 4 (very high), indicating potential injury or illness, significant property damage, business interruption, and temporary environmental effects. The key factors contributing to this high risk include: 1) The dimension of tapioca dust, which is less than 420 μm

(ranging from 12.66 to 25.79 μm); 2) Oxygen concentration, which can lead to dust explosions; 3) Confinement within enclosed spaces, such as the bucket elevator and large warehouse; 4) Dust dispersion caused by the hot surfaces of machinery; and 5) Ignition sources from human error (e.g., violation of safety standards) and machine error (e.g., bolts, nuts, and bearings). Figures 5 and Table 1 provide detailed findings.

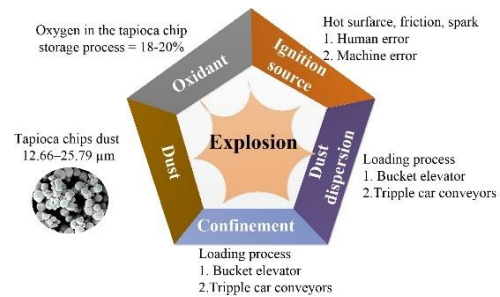


Figure 5. Shows risk identification dust explosion pentagon

Table 1. Shows risk identification and risk analysis using risk matrix

Main problems	Severity	Probability level	Risk level
1. Tapioca dust	4	4	4
- Dust dimation 12.66-25.79 μm			
2. Oxygen in the tapioca chip storage process	4	4	4
3. Confinement (bucket elevator and large warehouse)	4	4	4
4. Dust dispersion (oading process)	4	4	4
5. Ignition source			
Human error			
- Time pressures	4	2	2
- Stress	4	2	2
- Lack information	4	1	2
- Violation of safety standards	4	4	4
Machine error (hot surface, friction, spark)			
<i>Bucket elevator</i>			
- Bolts and nuts	4	4	4
- Rubber conveyor belt	4	2	2
- Bucket	4	2	2
- Static electricity	4	1	2
- Waste in the bucket elevator	4	1	2
<i>Tripper car conveyors and motor</i>			
- Motor gear	4	2	2
- Motor drive	4	1	2
- Bearing	4	4	4
- Set	4	2	2
- Roller	4	3	3
- Belt	4	3	3
- Pulleys	4	2	2

Table 2. Shows risk treatment applying the Hierarchy of Controls (HC)

Hierarchy of controls	Prevention item	Dust explosion prevention and mitigation	Remark
Elimination	Fuel Dispersion	1. Clean the storage area twice daily. 2. Install venting in the bucket elevator.	Monitoring / Review/ Training /
Substitution	Limiting Oxygen	Fire suppression (FS) Increase N ₂ /O ₂	Monitoring / Review
Engineering controls	Ignition Source Limiting Oxygen	1. Fire suppression (FS) 2. Explosion-wall (EW) 3. Explosion-proof equipment (EP)	Review / Improvement
Administrative controls	Ignition Source Dispersion	1. Process Hazard Analysis (PHA) 2. Job safety analysis (JSA) 3. Standard Operation Process (SOP) 4. Preventive Maintenance (PM)	Monitoring / Review / Training /

Table 3. Shows evaluation of dust explosion prevention using a protection factor

Protection factor	Before				After			
	Severity level	Likelihood level	Protection factor	Risk score	Severity level	Likelihood level	Protection factor	Risk score
Elimination								
1. Cleaning	4	5	0.9	18.0	4	5	0.1	2.0
2. Venting	4	5	1.0	20.0	4	5	0.1	2.0
3. Dust collector	4	5	1.0	20.0	4	5	0.1	2.0
Engineering								
1. FS	4	4	0.9	14.4	4	4	0.6	9.60
2. EP	4	5	1.0	20.0	4	5	0.6	12.0
3. EW	4	5	1.0	20.0	4	5	0.6	12.0
Administrative								
1. JSA	4	5	0.9	18.0	4	5	0.8	16.0
2. SOP	4	5	0.9	18.0	4	5	0.8	16.0
3. PHA	4	5	0.9	18.0	4	3	0.8	9.60
4. PM	4	5	0.9	18.0	4	5	0.8	6.0
Risk score average		18.44				9.72		
Hierarchy of hazard controls reduces the risk by 52.71%.								

Risk treatment

Risk treatment was employed to identify dust explosion prevention and mitigation measures based on the HC, which includes the following controls: 1) Elimination: Control dust accumulation and dispersion in the tapioca storage areas; 2) Substitution: Limit oxygen levels to prevent dust explosion conditions; 3) Engineering Controls: Control ignition sources through engineering solutions; and 4) Administrative Controls. Table 2 provides detailed findings.

Evaluation of dust explosion prevention

The evaluation of dust explosion prevention and mitigation, based on the HC, assessed its effectiveness using ten protection factors: cleaning, venting, dust collection, fire suppression, explosion walls, explosion-proof equipment, process hazard analysis, job safety analysis, standard operating procedures, and preventive maintenance. To assess risk, the following equation was used:

$$Risk = Severity \times (Probability \times Protection Fac)$$

For example, if the hazard related to dust accumulation has a severity rating of 4 and a

probability rating of 5, and the cleaning control measure (classified under administrative controls with PF = 0.90) is applied, the adjusted risk score would be:

$$Risk_{Cleaning} = 4 \times (5 \times 0.9) = 18$$

Initially, risk scores before any control measures were implemented ranged from 18 to 20 points. After implementing HC based interventions, the average risk score was reduced from 18.44 to 9.72, reflecting a 52.71% reduction in overall risk. Among all strategies, elimination controls were found to be the most effective, offering the greatest reduction in risk due to their low protection factor value (PF = 0.10). The summary of risk score changes before and after intervention is presented in Table 3.

Discussion

This study employed a risk matrix method to prioritize issues and propose prevention and mitigation strategies for dust explosions. This approach aligns with previous research that utilized risk matrix methods to prioritize radiological accident scenarios during nuclear power plant

deactivation, as well as risk assessments for oil and gas pipeline hot work using Analytic Hierarchy Process and fuzzy comprehensive evaluation (Ok *et al.*, 2022; He *et al.*, 2023). A key finding of this study is the dust explosion pentagon, which includes combustible dust, oxygen, confinement, ignition sources, and dust cloud formation (Wei *et al.*, 2020).

The primary cause of dust explosion risk in this study, similar to the findings of Amyotte and Eckhoff (2010), is ignition sources, which are essential components contributing to dust explosions. This investigation identified specific ignition sources, such as machine malfunctions (e.g., bearing failures) and human errors (e.g., violations of safety standards). This contrasts with the findings of Yuan *et al.* (2015b), who examined the risk of global dust explosions between 1785 and 2012. They identified ignition sources such as flames, direct heat, hot work, electric sparks, static electricity, impact sparks, self-heating and smoldering, friction sparks, hot surfaces, and other miscellaneous sources, none of which are attributed to human error (Yuan *et al.*, 2015b).

This contrast underscores the importance of integrating behavioral safety interventions alongside technical controls in dust explosion prevention strategies. The findings suggest that focusing solely on engineering controls, as emphasized by Yuan *et al.* (2015a), may be insufficient in environments where human interaction is frequent and procedural compliance is inconsistent. Therefore, reinforcing administrative controls, safety culture, and human reliability should be prioritized in tandem with technical measures to effectively mitigate explosion risks in similar industrial contexts.

The dust explosion severity in this study indicated that the highest risk level (extremely high risk) was assigned a score of 4 for severity, suggesting disabling injuries or diseases, significant property damage, company downtime, and chemical discharge with temporary environmental or public health consequences. This aligns with the impact of the 1997 dust explosion at a grain storage facility in Blaye, France, which resulted in significant damage and fatalities (van der Voort *et al.*, 2007). The HC was applied to manage the five key elements of dust explosions, and its effectiveness was evaluated using protection factors, leading to a 52.71% reduction in risk. A comparison of protection factor scores before and after implementation showed that elimination and engineering controls were more effective than administrative controls, consistent with the principles of the hierarchy of controls (Lingard *et al.*, 2014; Atkinson & Westall, 2010). However, when applying HC in practice, it is

important to understand its limitations, particularly its lack of specific measures. While standardized guides could address this, it is recommended to focus on general principles. This approach allows for context-based reframing of measures and subcategories, fostering the development of new legitimization practices (Ajslev *et al.*, 2022).

The risk assessment of dust explosions in the tapioca chip storage process and the implementation of preventive measures through the application the HC revealed that human error, specifically the violation of safety standards, was the leading cause with the highest probability of dust explosions. This finding contrasts with other studies that typically focus on machine errors. Therefore, selecting appropriate and comprehensive preventive measures that address the various risk factors is essential. In this study, the HC was applied to prioritize actions based on their effectiveness, from highest to lowest. While the HC can be applied in other workplaces, its effectiveness may vary depending on factors such as budget, personnel, and organizational context. Future studies should consider quantitative risk assessment methods to enhance the efficiency of dust explosion prevention, focusing on elimination, substitution, and engineering controls rather than relying heavily on administrative controls and personal protective equipment.

Risk ratings may be affected by subjective judgment in assigning severity, probability, and protection factor values. The implementation of higher-level controls like elimination and engineering may face financial and technical challenges. Administrative controls, while easier to apply, showed lower effectiveness in reducing risk. Future research should include multiple sites and use quantitative methods to improve accuracy and applicability.

Conclusions

This study emphasizes the practical value of applying a structured risk management approach, guided by the Hierarchy of Controls, to prevent dust explosions in the tapioca starch industry. By integrating multidisciplinary expertise and targeted control strategies, organizations can strengthen workplace safety and reduce the likelihood of catastrophic incidents. Future efforts should focus on sustaining engineering and elimination controls, enhancing employee awareness, and regularly reviewing risk management protocols to ensure continued effectiveness in dynamic industrial environments.

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