

RESEARCH ARTICLE

Determination of the prioritised factors influencing equipment failure in the process industry by applying the Delphi technique

Muhammad Danish Muhammad Yusri¹, Ibrahim Al Khowwas², Muhammad Fauzil Adzim², Azizan Ramli^{1*}

¹Faculty of Industrial Sciences and Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebu Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia

²Faculty of Vocational Studies, Universitas Airlangga, Jl. Dharmawangsa Dalam Selatan No.28-30, Surabaya, East Java 60286, Indonesia

Abstract - This study addresses the pervasive issue of equipment failure in industrial settings, acknowledging its potential impact on production, service delivery, cost of repairs, and, critically, employee health and safety. Accidents resulting from equipment failures, especially in the processing industry dealing with hazardous materials, can lead to catastrophic events such as explosions and fires. The root causes of equipment failure, as identified by previous research, encompass factors like improper operation, insufficient design, improper welding, and inappropriate materials. A significant portion (35.2%) of recorded accidents is attributed to equipment failure, while the remainder is linked to human or operational errors. Despite numerous studies identifying influencing factors, there exists a lack of prioritization, hindering effective resource allocation and action planning. The study sets out clear objectives: to identify, validate, and prioritize factors influencing equipment failure in the process industry. Utilizing the Delphi Technique, the research obtains expert opinions to rank these factors in three categories: human, mechanical, and external. Maintenance errors emerge as the most critical human factor, emphasizing their importance in preventing equipment failure. The rankings also underscore the pivotal roles of training, leadership, and top management in mitigating human-related risks. In the mechanical category, internal factors like shortages of material, corrosion, and degradation receive moderate rankings, while power problems are comparatively lower. External factors, such as external flammable sources, natural hazards, and contamination, are ranked lower, suggesting a relatively lower impact on equipment failure. The study concludes with the importance of adopting a multifaceted approach to reduce equipment failure, emphasizing strategies to minimize maintenance errors, enhance training, strengthen leadership, and address mechanical issues. The findings provide valuable insights for developing comprehensive risk management plans that consider both internal and external factors, serving as a guide for industry professionals and policymakers in proactively improving equipment reliability and reducing failures in the process industry.

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1. Introduction

Equipment failure occurs when a piece of equipment does not perform as intended [1]. However, failure does not necessarily mean that the equipment ceases to function entirely; rather, it results in a loss of its value as a capital investment for the company. Unplanned downtime for machines can significantly hinder productivity and make it harder to achieve production targets. Additionally, equipment failure can sometimes lead to accidental events. It is important to note that equipment failure is not a random incident; instead, it may be caused by a variety of factors [2]. If these contributing factors are identified and addressed, the likelihood of failure could be reduced or even avoided. This section reviews the existing literature to identify knowledge gaps and unresolved issues regarding the factors that influence equipment failures in the chemical industry [1]. Despite ongoing regulatory efforts, the accident rate in the chemical process industry (CPI) remains high, with complex operations and increased risks exacerbated by organisational restructuring and cost-cutting measures [3]-[4]. Human error is frequently cited as a primary cause of accidents across various sectors, including the chemical industry. Specifically, studies emphasised the considerable role of human error in accidents across sectors such as aviation, petrochemicals, traffic, steel and iron metallurgy, nuclear incidents, marine accidents, and chemical processes [5]-[9]. In the chemical industry, investigations into equipment-related accidents have revealed that failures in piping systems, heat-transfer equipment, and process vessels are significant contributors [10]. A detailed analysis of accident causes indicates that human and organisational factors account for 20% of failures, while technical factors contribute 78%. A systematic literature review (SLR) conducted between 2012 and 2022 identified three key themes related to equipment failure in the chemical industry: human factors (54%), mechanical factors (43%), and external factors (3%) [10]. Commonly used safety evaluation methods in chemical plant design include checklists, HAZOP, Layer of Protection Analysis (LOPA), hazard surveys, and safety reviews [11]-[12]. Nevertheless, these techniques have their limitations, particularly in the early stages of design [13].

Multi-criteria decision-making (MCDM) is essential for selecting optimal choices, and the Delphi Technique is chosen for its ability to iteratively gather and refine expert opinions [14]-[15]. There are still notable research gaps in the prioritisation of factors influencing equipment failure. This study seeks to address these gaps by applying the Delphi Technique to achieve consensus on the significance of identified factors, validate and enhance these factors, and uncover

any new or overlooked factors based on expert opinions [1],[3]-[4], [10], [16]. By doing so, this research contributes to a more comprehensive understanding of the factors influencing equipment failure in the chemical industry, thereby supporting better decision-making and mitigation strategies.

2. Materials and Methods

To establish a solid foundation for the literature review, it is essential to define clear and precise research questions. These questions guide the entire review process and ensure that the relevant topics are thoroughly explored. For example, one of the primary research questions could be: "What are the factors influencing equipment failure in the chemical process industry?" This question serves as a starting point for examining the diverse causes of equipment failure in the chemical industry. Other sub-questions may include inquiries into the roles of human error, organisational factors, and technological shortcomings in equipment failure, helping to narrow the scope of the review and focus on the most pertinent issues. In addition to defining the research questions, determining relevant search keywords is crucial for conducting a comprehensive literature search. These keywords serve as the basis for finding pertinent studies, articles, and research papers that contribute to understanding equipment failure in the chemical process industry. It is important to choose a variety of search terms that encompass a broad spectrum of concepts related to the topic. Keywords such as "contributors," "chemical process," "accidents," "equipment failure," and "risk factors" help identify relevant literature that covers not only the direct causes of failure but also the broader context in which these failures occur. Incorporating both technical and organisational terms ensures that the search captures a holistic view of the subject matter. Once the research questions and keywords have been established, the next step is to determine the criteria for selecting relevant studies. This step is crucial for ensuring that the literature reviewed is high-quality and directly addresses the research questions. Platforms such as ScienceDirect, ACS Publications, and Google Scholar can provide access to a wide range of scholarly resources, including peer-reviewed papers, articles, and conference proceedings. The selection process should involve establishing clear inclusion and exclusion criteria based on factors such as the study's relevance to the chemical process industry, the quality of the research methodology, the publication date, and the credibility of the journal or conference. By applying these criteria, the researcher can filter out studies that do not align with the study's objectives or that lack sufficient rigour, ensuring that only the most pertinent and reliable sources are included.

After selecting the relevant studies, the next step is to extract and analyse the data. This involves systematically gathering key information from the chosen research, including the causes of equipment failure identified in the studies, the methodologies used to investigate them, and the primary conclusions drawn from the research. Data extraction should be thorough, focusing on the most important aspects that contribute to understanding the factors leading to equipment failure. Once the data have been gathered, the analysis begins, including identifying common themes, patterns, and discrepancies across the studies. It is also essential to pinpoint knowledge gaps in the existing literature, as these gaps can highlight areas that require further research. Through this detailed analysis, the researcher can synthesise the information and draw meaningful conclusions that contribute to the broader understanding of equipment failure in the chemical industry. This process not only informs the literature review but also helps identify areas for future research, ultimately enhancing the body of knowledge in the field. Two experts from the relevant industry validate all the secondary data (a list of factors influencing equipment failure in the chemical industry) gathered and extracted from the literature review. In addition, they validate the open-ended questions presented to the Delphi experts during Delphi I. The list of factors and the open-ended questions were sent via email or WhatsApp for validation. A panel size of 4 must be considered the bare minimum [17]. As a result, this study conducted a Delphi survey with 5 industry experts serving as Delphi experts. The panel of experts for this study comprises individuals with relevant knowledge and expertise in process-industry equipment. The individuals involved in the data validation process may not be the same experts utilised for this purpose. These individuals were selected and invited to participate. Industry professionals, maintenance practitioners, and researchers are examples of potential experts.

2.1 Delphi Technique

2.1.1 Round 1

Each panel expert receives four open-ended online questions in this round. The panel of experts receive the questions through a Google Form. The question is as follows.

- 1) In your opinion, what are the factors influencing equipment failure in the process industry?
- 2) In your workplace, have you experienced any incidents related to equipment failure, and what are the contributing or main causes?
- 3) Do you have a competent or authorised person to handle and control this equipment?
- 4) Do you think leadership and top management contribute to safety interventions? If yes, why?

The list should be updated to include any new factors that are provided by the experts that are not already on the list of factors derived from the literature review.

2.1.2 Round 2

In this round, all the factors listed by the experts and identified in the secondary data were combined into a single list and included in the questionnaire via Google Forms. In the questionnaire, the experts were asked to rate the factors based on their importance in influencing equipment failure in the chemical process industry using a 5-point Likert scale (1-strongly disagree, 2-disagree, 3-neutral, 4- agree, 5-strongly agree).

2.2 Analysis of data

The 5-point Likert scale questionnaire administered to the Delphi experts during Delphi II was analysed using the median, interquartile range (IQR), and frequency percentages. The median denotes the middle value, whereas the IQD indicates the degree of similarity among experts' responses and indicates whether consensus was achieved. A consensus was reached when the IQD was at or below 1. A frequency of 75% or higher should be regarded as a consensus [18]. The Delphi II data was processed using Microsoft Excel. Multiple interpretations exist for determining consensus in Delphi I to achieve agreement among the experts. Figure 1 illustrates the prescribed procedures proposed by previous researchers for establishing consensus using the Delphi technique. The study's flowchart is shown in Figure 2.

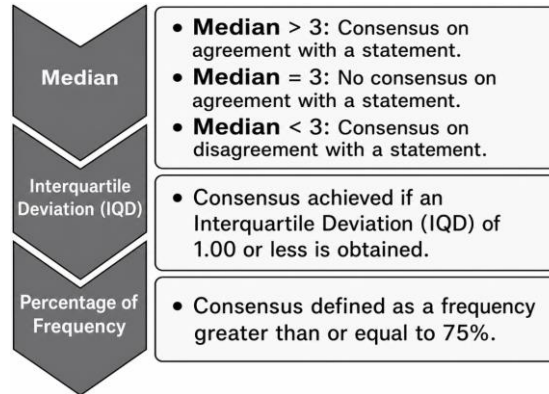


Figure 1. Determination of consensus for the Delphi technique

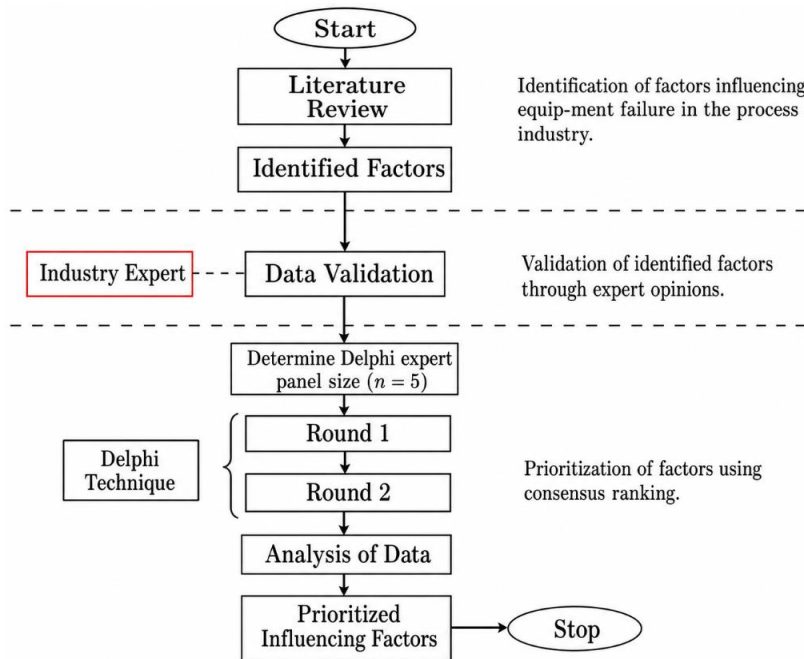


Figure 2. The flowchart of the study

3. Results and Discussion

The review of the relevant literature identified several articles that outlined a wide range of factors influencing equipment failure in the chemical process industry. Based on previous studies, 18 factors were identified. These elements were discovered through research conducted between 2011 and 2022. As shown in Table 1, the findings for the 18 factors are presented along with their definitions.

In the Delphi II process, the same five experts who participated in the Delphi I process were engaged to analyse the factors influencing equipment failure in the process industries. The twenty (20) factors gathered from the literature review and the open-ended questions in the Delphi I questionnaire were used to construct twenty (20) questions for the Delphi II questionnaire. The purpose of these questionnaires was to determine whether the experts agreed with the identified factors. A five-point Likert scale was used for the questionnaire ratings. On this scale, a rating of "5" indicated "strongly agree," a rating of "4" indicated "agree," a rating of "3" indicated "neutral," a rating of "2" indicated "disagree." A rating of "1" indicated "strongly disagree."

Table 1. List of factors

Factors	Definition
1. Human error	Errors made by people while using, maintaining, or using other equipment. It can cover a wide range of mistakes, from oversights in procedure to errors in judgment.
2. Design error	Describes errors or defects in the initial planning of a piece of equipment that might result in problems like inefficiency, safety risks, or early failure.
3. Lack of supervision	Poor supervision of equipment maintenance or operation can result in mistakes going unreported or unchecked, which may eventually cause problems.
4. Lack of training	Personnel with insufficient training may not completely comprehend how to maintain or operate equipment, which increases the chance of mistakes or accidents.
5. Maintenance error	Errors made during equipment maintenance, such as improper service, insufficient inspections, or the use of improper processes, can lead to equipment failure.
6. Power problem	Electrical and electronic equipment can be affected by problems with the power supply, such as voltage fluctuations, electrical surges, or blackouts.
7. Shortage of materials	Unplanned downtime may result from a lack of essential materials required for equipment operation or maintenance.
8. Corrosion	Equipment can become weaker and have a shorter lifespan as a result of the progressive degradation of materials brought on by chemical interactions with the environment, such as rusting.
9. Degradation	Refers to the general wear and tear that equipment experiences over time, which causes a loss in performance or functioning.
10. Overpressure	Using equipment past its intended pressure ranges may cause structural problems, leaks, or ruptures.
11. Overheat	Excessive heat can harm equipment parts, which can result in malfunctions or even fires.
12. Heat transfer	Performance and dependability of equipment can be impacted by problems with heat transmission, such as ineffective cooling or heating procedures.
13. Flow related	Equipment failure can be caused by issues with the flow of materials or fluids through a piece of equipment, such as blockages, leaks, or inefficient flow.
14. Construction material	The type of materials used to build an item can affect how durable, corrosion-resistant, and long-lasting it is.
15. Vibration	Uncontrolled or excessive vibrations can cause mechanical stress, damage, and ultimately component failure.
16. External flammable sources	Outside of a piece of equipment or a facility but with the ability to interact with that equipment or facility in a way that could cause fires or explosions are sources of flammable materials or chemicals.
17. Natural hazard	Natural hazards can harm equipment and cause operations to be disrupted, including earthquakes, floods, hurricanes, and tornadoes.
18. Contamination	Impurities, foreign objects, or other substances introduced into equipment can impair its functionality and cause defects or breakdowns.

Table 2 displays the analysis of the Delphi II survey and the evaluations for each factor. The results present a thorough analysis of the Delphi II survey using measures such as the median, interquartile range (IQD), and percentage distributions. This approach provides a clear picture of the expert evaluations for each factor, offering valuable insights into the factors influencing equipment failure in the process industry. The combined analysis from Delphi II presents a comprehensive examination of various factors influencing equipment failure, offering insights that do not explicitly categorise into human, mechanical, or external themes. Among the human and organisational factors, Lack of Training, Leadership, Top Management, Maintenance Error, Human Error, and Design Error achieved unanimous agreement across all measures, including median, IQD, and frequency percentage, reflecting robust 100% consensus among the experts. Notably, Lack of Supervision, while not reaching a unanimous agreement, still garnered a significant 60% agreement rate, highlighting some level of consensus within the group.

When examining the mechanical factors, including power problems, material shortages, corrosion, degradation, overpressure, overheating, heat transfer, flow-related issues, construction materials, and vibration, a strong consensus emerged, with 90% agreement based on median scores and an IQD cut-off of ≤ 1 . Despite this consensus, certain mechanical factors, specifically overpressure, overheat, heat transfer, and flow-related factors, did not achieve full consensus, with only 60% agreement among participants. This suggests that while there is general agreement, some factors still do not fully align among the experts. In the domain of external factors, including External Flammable Sources, Natural Hazards, and Contamination, a unanimous 100% consensus was reached based on an $\text{IQD} \leq 1$. However, the agreement on median scores showed some variability: only one factor achieved full consensus, while others did not reach unanimity.

Table 2. List of evaluated factors

Factors	Question	Median	IQD	Percentage of frequency (Agree & strongly agree)
1. Human error	To what extent do you agree that human error, defined as errors made by individuals while using, maintaining, or operating equipment, significantly influences equipment failure in the process industry?	4	1	80%
2. Design error	How much do you agree that flaws or defects in the initial planning or design of equipment significantly contribute to equipment failure in the process industry?	4	1	80%
3. Lack of supervision	To what extent do you disagree that adequate monitoring of equipment maintenance or operation fails to significantly contribute to issues and potential equipment failure in the process industry?	4	1	60%
4. Lack of training	To what degree do you agree that inadequate training for personnel, resulting in a lack of comprehension in equipment maintenance or operation, significantly influences equipment failure in the process industry?	5	1	100%
5. Leadership	Does leadership quality affect process industry equipment failure through safety protocols, maintenance resource allocation, and accountability culture?	5	1	100%
6. Top management	Do you agree that top management decisions about resource allocation, safety protocols, maintenance programs support, and safety-oriented culture directly affect industrial equipment failure?	5	1	100%
7. Maintenance error	Do you agree that errors made during equipment maintenance, such as improper service, insufficient inspections, or the use of improper processes, can lead to equipment failure?	5	0	100%
8. Power problem	Do you totally agree that issues related to power supply, including voltage fluctuations, electrical surges, or blackouts, significantly influence equipment failure in the process industry?	4	1	60%
9. Shortage of materials	Do shortages of essential materials for equipment operation or maintenance significantly affect process industry equipment failure?	4	0	80%
10. Corrosion	Do you think corrosion, caused by chemical reactions with the environment such as rusting, affects process industry equipment failure?	5	1	100%
11. Degradation	In the process industry, wouldn't you agree that equipment degradation, encompassing the general wear and tear leading to a decline in performance or functionality over time, can significantly influence equipment failure?	4	0	100%
12. Overpressure	To what extent do you agree that overpressure, resulting from using equipment beyond its intended pressure ranges, significantly influences equipment failure in the process industry?	4	2	60%
13. Overheat	How much do you disagree that overheating, which damages equipment parts and can cause malfunctions or fires, does not significantly affect process industry equipment failure?	4	1	60%
14. Heat transfer	To what degree do you believe that challenges associated with heat transmission, such as ineffective cooling or heating procedures, impact equipment failure in the process industry?	4	1	60%
15. Flow related	How much do you believe that issues linked to the movement of materials or fluids through equipment, including blockages, leaks, or inefficient flow, contribute significantly to equipment failure in the process industry?	4	1	60%
16. Construction material	Do you agree that the choice of construction materials used in building equipment significantly influences equipment failure in the process industry, affecting durability, corrosion resistance, and longevity?	4	0	100%
17. Vibration	Uncontrolled or excessive vibrations can cause mechanical stress, damage, and ultimately component failure which directly influences equipment failure?	4	1	100%
18. External flammable sources	To what degree do you agree external sources of combustible materials or chemicals that could cause fires or explosions affect process industry equipment failure?	3	1	40%
19. Natural hazards	Do natural hazards, such as earthquakes, floods, hurricanes, and tornadoes significantly affect process industry equipment failure and operational disruptions?	3	1	40%
20. Contamination	Do you agree that contaminants, foreign objects, and other substances introduced into process industry equipment significantly affect functionality and cause defects or breakdowns?	4	1	60%

Table 3. Consensus ranking

Factors	Ranking								
	1	2	3	4	5	6	7	8	9
1. Human error						X			
2. Design error						X			
3. Lack of supervision							X		
4. Lack of training		X							
5. Maintenance error	X								
6. Leadership		X							
7. Top management		X							
8. Power problem							X		
9. Shortage of material				X					
10. Corrosion		X							
11. Degradation			X						
12. Overpressure								X	
13. Overheat							X		
14. Heat transfer							X		
15. Flow related							X		
16. Construction material			X						
17. Vibration					X				
18. External flammable sources									X
19. Natural hazard									X
20. Contamination							X		

Furthermore, none of the external factors attained a frequency of 75% or higher (agree or strongly agree), as recommended by previous studies [18]. As a result, these factors did not reach consensus on their frequency, indicating that the experts were less unified in their assessment of the significance of external factors than of human and mechanical factors. For complex issues or decision-making processes, the Delphi Technique is a widely used method for gaining insights and reaching consensus among experienced individuals. To determine the order of importance of factors affecting equipment failure in the process industry, Table 3 presents the consensus ranking of all 20 factors across the three primary categories.

In the Human Factor category, the rankings indicate that maintenance errors are the most influential factor in equipment failure. Therefore, it is ranked at the top of the list. This indicates that experts agree that errors during maintenance procedures significantly impact the reliability and performance of the equipment. Furthermore, factors such as a lack of training, leadership, and top management are ranked second, indicating their substantial importance. Mitigating the risks of equipment failure caused by human factors highlights the critical roles of comprehensive training programs, effective leadership, and competent management. The rankings for the Mechanical Factor category, on the other hand, span a wide range of importance. It would appear that “power problems”, which are ranked seventh, are less significant in comparison to other factors that fall under this category. On the other hand, vibration, corrosion, degradation, construction materials, and material shortages all rank in the middle (ranging from second to fifth on the list). Even though these mechanical issues are significant contributors to equipment failure, they may not be as high a priority as maintenance-related concerns. External factors, including natural hazards, contamination, and flammable sources, are ranked ninth and seventh, respectively, indicating they are perceived to have less impact than internal factors. This suggests that external factors may not be significant contributors to equipment failure compared with internal factors. There is a clear consensus among experts on the criticality of maintenance errors and the importance of addressing issues in training, leadership, and top management to prevent equipment failure in the process industry. The data indicate this. The perceived importance of mechanical factors varies power problems are ranked lower than other factors, although they are essential.

Regarding factors that influence equipment failure, external factors are considered less significant than internal factors, though they remain relevant. However, a limitation of this study is its exclusive focus on the chemical industry, which prevents the identification and prioritisation of factors influencing equipment failure in other sectors. Additionally, only experts from the chemical industry were invited to participate. To address this, it is recommended that future research expand its scope to include other industries and apply the same Delphi method. The primary focus areas for preventing equipment failure in the process industry would include stringent measures to minimise maintenance errors, enhanced training programs, strengthened leadership capabilities, addressing mechanical concerns related to materials and vibrations, and considering, but not overemphasising, external factors such as flammable sources, natural hazards, and contamination. These considerations would be based on the Delphi Technique, which utilised the rankings that were provided. This all-encompassing approach is expected to help reduce the frequency of equipment failures and the severity of their effects.

4. Conclusions

The comprehensive ranking data provides valuable insights into the factors influencing equipment failure in the process industry, addressing the study's main objective of identifying and ranking these factors through expert opinions using the Delphi Technique. The study successfully categorised these factors into human, mechanical, and external categories, highlighting the various elements affecting equipment dependability. The rankings reveal that, within the Human Factor category, maintenance errors are the most significant, underscoring the importance of error-free maintenance practices to prevent equipment failure and emphasising the critical roles of training, leadership, and top management in mitigating human-related risks. In the Mechanical Factors category, issues such as material shortages, corrosion, degradation, vibration, and construction material quality were ranked moderately, with power problems receiving a lower ranking, suggesting a lesser impact. External factors such as flammable sources, natural hazards, and contamination were ranked lower, indicating that internal factors have a greater influence on equipment failure. Overall, the study highlights that reducing equipment failures requires a multifaceted approach that focuses on reducing maintenance errors, improving training, strengthening leadership, resolving mechanical issues, and considering external factors. The Delphi Technique proved effective in gathering expert opinions and achieving consensus on the most significant factors, providing valuable guidance to industry professionals and policymakers for implementing targeted interventions and preventive measures to improve equipment reliability and reduce failures in the process industry.

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Declaration of Competing Interest

The author declares no conflicts of interest.

CRedit Authorship Contribution Statement

Muhammad Danish Muhammad Yusri: Methodology, Investigation, Writing-original draft

Ibrahim Al Khowwas: Analysis, review & editing

Muhammad Fauzil Adzim: Analysis, review & editing

Azizan Ramli: Conceptualisation; Review & editing, Validation, Supervision.

Availability of Data and Materials

The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations

This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations

The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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