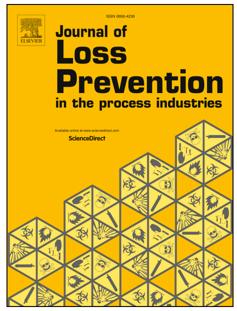

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Risk assessment of safety level in university laboratories using questionnaire and Bayesian network

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Abstract:

Accidents in university laboratories not only create a great threat to students' safety but bring significant negative social impact. This paper investigates the university laboratory safety in China using questionnaire and Bayesian network (BN) analysis. Sixteen influencing factors for building the Bayesian net were firstly identified. A questionnaire was distributed to graduate students at 60 universities in China to acquire the probability of safe/unsafe conditions for sixteen influencing factors, based on which the conditional probability of four key factors (human, equipment and material, environment, management) was calculated using the fuzzy triangular theory and expert judgment. The determined conditional probability was used to develop a Bayesian network model for the risk analysis of university laboratory safety and identification of the main reasons behind the accidents. Questionnaire results showed that management problems are prominent due to insufficient safety education training and weak management level of management personnel. The calculated unsafe state probability was found to be 65.2%. In the BN analysis, the human factor was found to play the most important role, followed by equipment and material factor. Sensitive and inferential analysis showed that the most sensitive factors are personnel incorrect

operation, illegal operation, and experiment equipment failure. Based on the analysis, countermeasures were proposed to improve the safe management and operation of university laboratories.

Keywords: University laboratory safety; Bayesian network; Questionnaire investigation; Risk assessment

1. Introduction

University laboratories provide important place for academics and graduate students to conduct scientific experiments. In recent years, the number of graduate students enrolled in China has increased significantly, from 0.129 million in 2000 to 1.177 million in 2021 (Ministry of Education of the People's Republic of China, 2001; Ministry of Education of the People's Republic of China, 2022). As the number of graduate students continues to increase, the conditions of university laboratories (such as space, laboratory assistant) could not meet the research demand resulting in unsafe behaviour and potential hazards. Particularly, exploratory experiments conducted in university laboratories often lack a detailed risks analysis with unknown safety hazards. Moreover, the personnel density in many laboratories is high, with the potential to cause serious consequence and a larger number of casualties in case of an accident. For example, a serious explosion of magnesium powder during the landfill leachate occurred at a laboratory of Beijing Jiaotong University in 2018, in which three students were killed (Yang et al., 2019). More recently, a deflagration due to magnesium aluminium powder occurred in a laboratory of Nanjing University of Aeronautics and Astronautics, resulting in 2 deaths and 9 injuries (Yang et al., 2022). These accidents highlight the great significance to acquire information on the current situation of university laboratories in China and to determine key influencing factors in the management and operation of these laboratories.

The safe management and operation of university laboratories has attracted much attention. Nasrallah et al. (2022) investigated the accident rate in the scientific laboratories of Lebanese public universities by distributing 220 questionnaires on personal information, workplace risks and safety training. The results showed that the lack of targeted training was the primary reason for the high accident rate. Samaranayake et al. (2022) investigated the culture level in Sri Lankan industrial chemical laboratories by interviewing laboratory supervisors. They found that the laboratory culture level was low because of the unclear safety inspection subject. Olewski and Snakard (2017) analysed a process safety management system in university laboratories and emphasized that everyone should take corresponding responsibilities, not just management personnel. Bai et al. (2022) conducted a statistical analysis of 110 laboratory accidents in China during the past 20 years. In their analysis, the relation between the occurred accidents and (a) time, (b) laboratory types and (c) cause contributions were explored. The results showed that the number of reported accidents displays an overall decreasing trend after a steady growth period before 2010. In terms of the laboratory type, chemical laboratories have the highest number of accidents, whereas in terms of cause contributions, human factors are the most significant one, and the training element was found to be vulnerable in laboratory management. Peng et al. (2019) calculated the laboratory safety risk in Southwest University by safety checklist, the fuzzy analytic hierarchy process and machine learning. They found that the laboratory was at a relatively safe level, but professional skills and emergency response of students were still insufficient. Li et al. (2021) established a semi-quantitative safety index model based on the Matter-Element Extension Theory to assess the key factors affecting laboratory safety. They found that the violation of operating procedures and the improper storage and use of chemicals are the main causes of accidents. These studies showed that questionnaires are an effective method to study university laboratory safety. Other models and semi-quantitative analytical methods, such as analytic hierarchy process (AHP), have also been developed to evaluate university laboratory safety and study specific influencing factors. However, the relative importance of these factors (human, machine, environment, and management) is still unknown, which could result in difficulties in the management and operation of laboratories.

A Bayesian network (BN) is a system evaluation method, which can show the sensitivity and relative importance of each variable (influencing factors) (Moradi et al., 2022). BN has been widely used for the risk assessment in different industries, such as ship, aviation, mining, etc. Aydin et al. (2021) established a BN on the ship collision in narrow waters and 35 nodes (influencing factors) were built and analysed. They found that inadequate communication with other ships played an important role in the collision. Zhang and Mahadevan (2021) discussed 740 influencing factors in the aircraft damage and personnel injury analysis by combining accident reports and BN. They found that improper engine instrument operation and oil placement are the most important factors. Li et al. (2021) analysed the probability of aluminium production explosion accidents with 29 influencing factors by combining fault tree analysis and a BN model. They provided the top five key influencing factors, including wet ladles and tools use, ground gathered water, tap hole breakage, casting mould damage, and circulating water leakage. Li et al. (2020) assessed the risk of gas explosion with 18 influencing factors for Babao Coal Mine in China based on a fuzzy analytic hierarchy process and BN. The results showed that the failure of the fan and electrical failure are the top two influencing factors.

Whilst BN has been widely used for risks analysis of complex systems which are comprised of multiple influencing factors, studies on the safety in university laboratories using BN are still limited. The safety of university laboratories generally consists of four key aspects, i.e., human, equipment, environment, and management, all of which can have their own affecting factors. Ma et al. (2022) found that lack of laboratory safety culture was the most fundamental factor contributing to fire and explosion accidents based on a fuzzy analytic hierarchy process (FAHP) and BN. Zhang et al. (2020) found that personnel were the main influencing factor based on BN for assessing gas leakage in university laboratories. A human factor analysis and classification system for university laboratories (HFACS-UL) model was combined with a fuzzy BN to analyse the safety level of university laboratories (Li et al., 2022). In the BN, expert judgment and fuzzy set theory were often used to overcome the problem of insufficient historical accident data or non-disclosure of accident data, and to determine the probability of occurrence of influencing factors (Zhang et al., 2014). However, one of the limitations of these methods is that the prior probability is primarily determined from expert judgment and thus has a high level of subjectivity, resulting in large randomness of the prior probability, which would have a significant impact on the subsequent BN analysis. Therefore, it is necessary to find a method to determine the prior probability with objectivity. Based on the studies on the safe management and operation of university laboratories, questionnaires have been used for studying university laboratory safety and the results in four key aspects, including human, equipment, environment, and management can be used to describe the current situation of university laboratory safety. Thus, the results of questionnaire can be combined with BN to determine prior probability, in which the results of questionnaire can be used to solve the problem about the lack of objectivity for prior probability in the BN analysis.

This paper utilizes a combination of questionnaires and a fuzzy BN to evaluate the safety level of university laboratories in China. The questionnaire focused on the current situation of the safety level from the perspective of Chinese graduate students. Prominent problems from questionnaire results on four key aspects were analysed. The questionnaire results were also used to determine the probability of the influencing factors objectively. BN and fuzzy theory were then combined to determine the conditional probability of four key factors (human, equipment and material, environment, management), which was in turn used to build a Bayesian network model for the risk analysis of university laboratory safety and examination of the main reasons behind the accidents.

2. Methodology

2.1. Bayesian network

Bayesian network (BN), also known as belief network, is a directed acyclic graphical model that describes the relationship between data variables (Pearl, 1985). A BN is composed of nodes, arcs and conditional probabilities. Among nodes representing random variables, a parent node represents the cause and a child node the consequence, which are connected by an arc. In the BN analysis, the joint probability distribution of each variable is related to the conditional probability of its parent nodes as:

$$P(X) = P(X_1, X_2, X_3, \ldots, X_n) = \prod_{i=1}^{n} P(X_i \mid Pa(X_i)) \tag{1}$$

where $Pa(X_i)$ is the parent set of variable X_i.

The prior probability can be updated dynamically by setting an evidence node (E). If the probability of the evidence node (E) is changed, the probabilities of other nodes in the BN will be updated to obtain the posterior probabilities as:

$$P(X \mid E) = \frac{P(X,E)}{P(E)} = \frac{P(X)P(E|X)}{\sum_{i=1}^{n} P(E|X_i)} \tag{2}$$

where $P(X)$ and $P(E)$ are prior probabilities, $P(E \mid X)$ is a prior conditional probability, and $P(X \mid E)$ is a posterior conditional probability to be calculated.

2.2. Questionnaire

The questionnaire focused on the four key aspects including human, machine, environment, and management, for which a total of 21 questions were set as shown in the Supplementary Material. The questionnaire was distributed to graduate students in the science and engineering disciplines at 60 universities in China by Sojump App. A total of 912 responses were returned, out of which 740 were validated after statistically collating each of the questionnaire questions. Due to the large number of responses received, only the responses with all questions completed were used for data analysis. Furthermore, to ensure that the students have read the questions before answering them, a random question was included in the middle of questionnaire "Please choose Management in the following options". If a participant chose any other option, that questionnaire would be deemed invalid. The participant was informed before they completed the questionnaire that their participation is completely voluntary, and all the data obtained would be anonymised. The distribution conditions of the participants were identified by their IP address as shown in Fig.1. Participants are from almost all regions of China, with a stronger presence at the regions with good education resources.

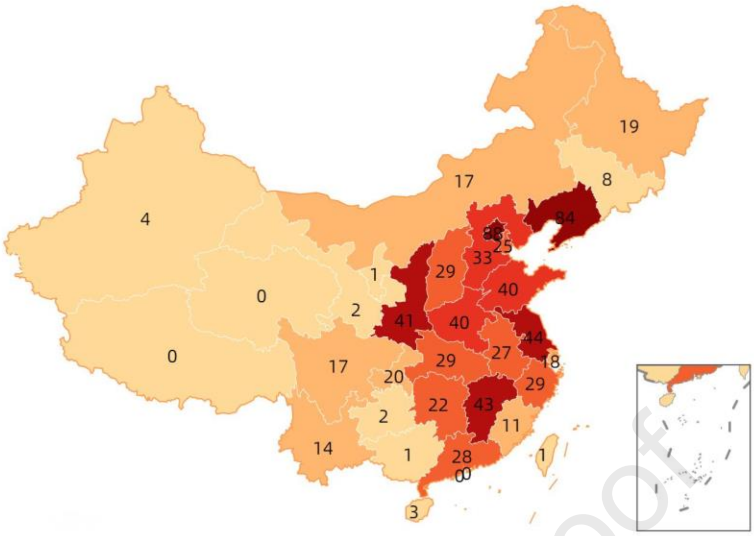

Fig.1. Number and distributions of participating graduate students

2.3. Probability analysing model

2.3.1. Triangular fuzzy theory

A fuzzy set theory studies phenomena through fuzzy numbers and establishing membership functions (Zadeh, 1965). In the risk assessment, fuzzy language in the triangular fuzzy theory can be used and then transformed into the conditional probability of BN (Senol& Yasli, 2021). The triangular fuzzy theory is used in this study because it is particularly suitable in situations where the available data is limited, and its calculations are also relatively simple (Sadat & Derakhshani, 2023). Additional calculations using the trapezoidal fuzzy theory also confirmed that the difference in the results obtained with the two fuzzy theory functions are negligible. A combination of expert judgment and triangular fuzzy theory is used in this work. The membership functions of the triangular fuzzy numbers are given in Eq. (3), for a triangular fuzzy number $\mathrm{A} = (a, b, c)$.

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a}, & x \in (a, b) \\ \frac{c-x}{c-b}, & x \in (b, c) \\ 0 & , otherwise \end{cases} \tag{3}$$

where a, b and c represent the lower least likely value, the most likely value, and the upper least likely value, respectively.

For two triangular fuzzy numbers $\widetilde{\mathrm{A}_1} = (a_1, b_1, c_1)$ and $\widetilde{\mathrm{A}_2} = (a_2, b_2, c_2)$, we have:

$$\begin{cases} \widetilde{A_1} \oplus \widetilde{A_2} = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \\ \widetilde{A_1} \ominus \widetilde{A_2} = (a_1 - a_2, b_1 - b_2, c_1 - c_2) \\ \widetilde{A_1} \otimes \widetilde{A_2} = (a_1 a_2, b_1 b_2, c_1 c_2) \\ \lambda \otimes \tilde{A} = (\lambda a, \lambda b, \lambda c) \end{cases} \tag{4}$$

2.3.2. Expert judgment weight

In the traditional expert judgment process, the weight of experts was assumed to the same, ignoring personal differences such as education background, work experience, etc (Yu et al., 2021). However, as demonstrated in (Li et al., 2019), it is important to ensure the objectivity of expert judgment when calculating the conditional probability and that the evaluation data should be modified by considering comprehensive factors of experts. In this study, the expert weight was determined according to three criterions of job position, education level and years of work as shown in Table 1.

Table 1. Specific criterion of expert weight

Criterion type	Description	Score
Job position	Professor	5
	Associate professor	4
	Engineer	3
	Technician	2
	Worker	1
Education level	PhD	4
	Master	3
	Bachelor	2
	High school and below	1
Years of work	＞30 years	5
	20~30 years	4
	10~20 years	3
	5~10 years	2
	＜5 years	1

The total score and weight of each expert can be found using Eqs. (5) and (6) respectively:

$$S_i = S_{pi} + S_{ei} + S_{yi} \tag{5}$$

$$W_i = \frac{S_i}{\sum_{i=1}^{n} S_i} \tag{6}$$

where S_i is the total scores of ith expert weight; S_{pi}, S_{ei} and S_{yi} are scores of job position, education level and years of work of the ith expert, respectively; W_i is the weight of ith expert; n is the number of experts.

2.3.3. Aggregation of expert judgments

After obtaining the weight of experts, experts were invited to judge the probability of intermediate nodes using fuzzy linguistic description in five categories (Very Low, Low, Medium, High and Very High). Different triangular fuzzy numbers corresponding to the detail fuzzy linguistic description are shown in Table 2.

Table 2. Fuzzy linguistic description

Linguistic description	Triangular fuzzy numbers
Very Low (VL)	(0,0.1,0.2)
Low (L)	(0.2,0.3,0.4)
Medium (M)	(0.4,0.5,0.6)
High (H)	(0.6,0.7,0.8)
Very High (VH)	(0.8,0.9,1.0)

Based on the weight of experts, the probability of intermediate nodes can be calculated as:

$$A = \sum_{i=1}^{n} (W_i \times A_i) \tag{7}$$

where A is the aggregation of fuzzy triangular numbers for a given intermediate node; A_i is the fuzzy triangular numbers of i[th] expert fuzzy linguistic description.

2.3.4. Defuzzification

After acquiring the aggregation of triangular fuzzy numbers $A = (a, b, c)$, the centre of area (COA) of defuzzification was used to transform A into its crisp fuzzy value A'. For any given node, there are two different possible states in the conditional probability: safe and unsafe, and the probability of each possible state needs to be calculated.

The triangular fuzzy number $A = (a, b, c)$ of one state for a node was transformed into its crisp fuzzy value A' (Facchinetti et al., 1998).

$$A' = \frac{a+2b+c}{4} \tag{8}$$

The fuzzy value of different possible states for this node needs to be normalized to satisfy the uniformity of the probabilities and the value after normalization can then be taken as the probability of that state as:

$$P_j = \frac{A'}{\sum_{j=1}^{m} A'} \tag{9}$$

where P_j represents the probability of one state in a node after normalization; A'

represents the fuzzy value of this state; m is the number of different states in this node.

2.4. Framework

The study framework is shown in Fig. 2. The first step is the risk identification using data collected from questionnaires, which reveals the potential influencing factors related to laboratory safety. The second step is to establish a BN, in which the probability of the sixteen risk factors is determined based on the questionnaire results and the conditional probability of four key factors (human, equipment and material, environment, management) using the triangular fuzzy theory. The third step is to analyse the results of BN (causal, inferential and sensitivity analysis). In the final step, corresponding safety countermeasures are proposed for the improvement of university laboratory safety.

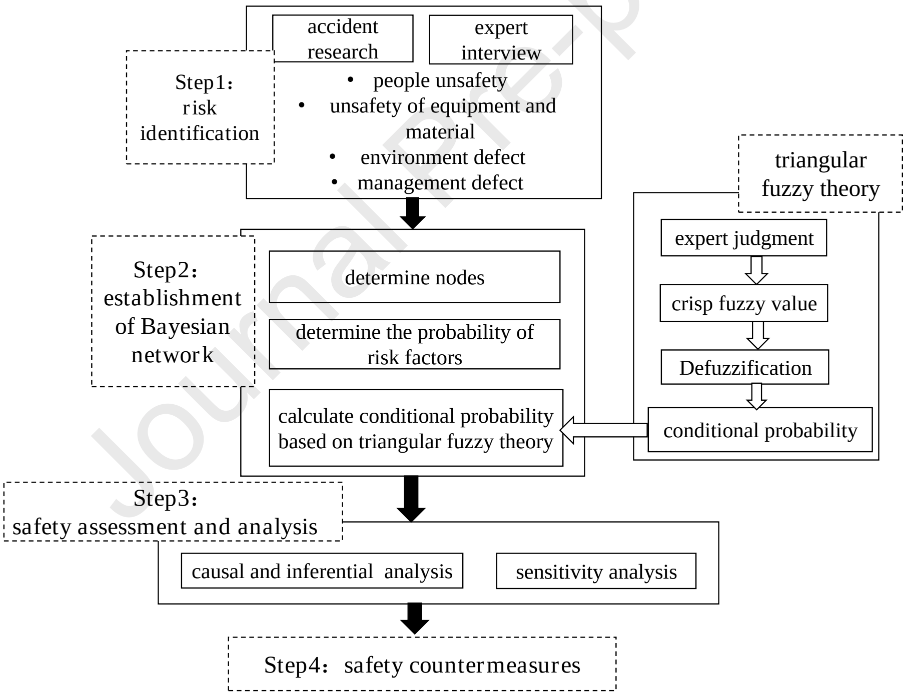

Fig. 2. Framework for risk analysis of university laboratory safety

3. Results and Discussion

3.1. Risk identification

The causes of accidents in Chinese university laboratories in the last two decades were investigated. Ten experts were interviewed to identify potential risks from the key four aspects and the identified risk factors with corresponding descriptions are summarized in Table 3. It should be noted that when designing the questionnaire, four options were provided for all questions. However, during the collation process, the probability of some of options is very close to 0 (i.e., option of no significant importance), which was subsequently combined with some of the other options for clearer presentation of the results.

Table 3. Risk factors of university laboratory

Factor	Risk Factor	Description	State
Human factor (R_1)	Low safety awareness level (R_{11})	Laboratory personnel don't report experiment to managers before the experiment and so on.	Yes No
	Incorrect operation (R_{12})	The wrong ratio of experimental reagents or the wrong operation of experimental equipment.	Frequently Occasionally Rarely Never
	Illegal operation (R_{13})	Laboratory personnel leave their posts without authorization, or don't wear protective articles or other acts in violation of the operating procedures.	Frequently Occasionally Never
	Weak emergency response capacity (R_{14})	The emergency response measures aren't carried out appropriately when laboratory personnel are faced with emergencies.	Yes No
Equipment and material factor (R_2)	Basic information of experimental equipment (R_{21})	Purchase source, manufacturer qualification, safety performance and other basic information of experimental equipment.	Good Poor
	Experimental equipment failure (R_{22})	The experimental equipment malfunctions during the experiment.	Frequently Occasionally Rarely

			Never
	Soundness of personal protective equipment (R_{23})	Completeness of personal protective equipment such as protective masks and gloves.	Good Poor
	Storage and use of dangerous goods (R_{24})	Special personnel shall be assigned to take care of and report the use of dangerous goods.	Good Poor
Environment factor (R_3)	Mixed use of laboratory layout (R_{31})	Mixed use of space as laboratory and office.	Frequently Occasionally Never
	Improvement of firefighting facilities (R_{32})	Fire hydrant and other firefighting facilities in the laboratory.	Good Poor
	Different experiments are carried out simultaneously in the same room (R_{33})	During the experiment, multiple groups of experiments in the same room are carried out in parallel.	Frequently Occasionally Rarely Never
	Laboratory safety atmosphere (R_{34})	Striking safety warning signs in the laboratory and so on.	Perfect General Poor
Management factor (R_4)	Information platform construction (R_{41})	Information platform construction for laboratory experiment reporting and dangerous goods procurement.	Good Poor
	Rationality of rules and regulations (R_{42})	Laboratory rules and regulations are reasonable for carrying out.	Unreasonable Reasonable
	Management level of management personnel (R_{43})	Full-time management personnel inspect the laboratory strictly.	Tight General Loose
	Safety education and training and emergency drill (R_{44})	Safety education and training and emergency drills are carried out for	Frequently Occasionally

	universities laboratories.	Rarely Never

3.2. BN of university laboratory safety

3.2.1. BN model establishment

Based on the factors determined from risk identification, a BN can be established. In the analysis, the risk factors (R_{11}~R_{44}) represent parent nodes, whereas (R_1~R_4), namely human, equipment and material, environment and management factors, are intermediate nodes. Based on the interdependence among these factors, the BN net can be built as shown in Fig. 3.

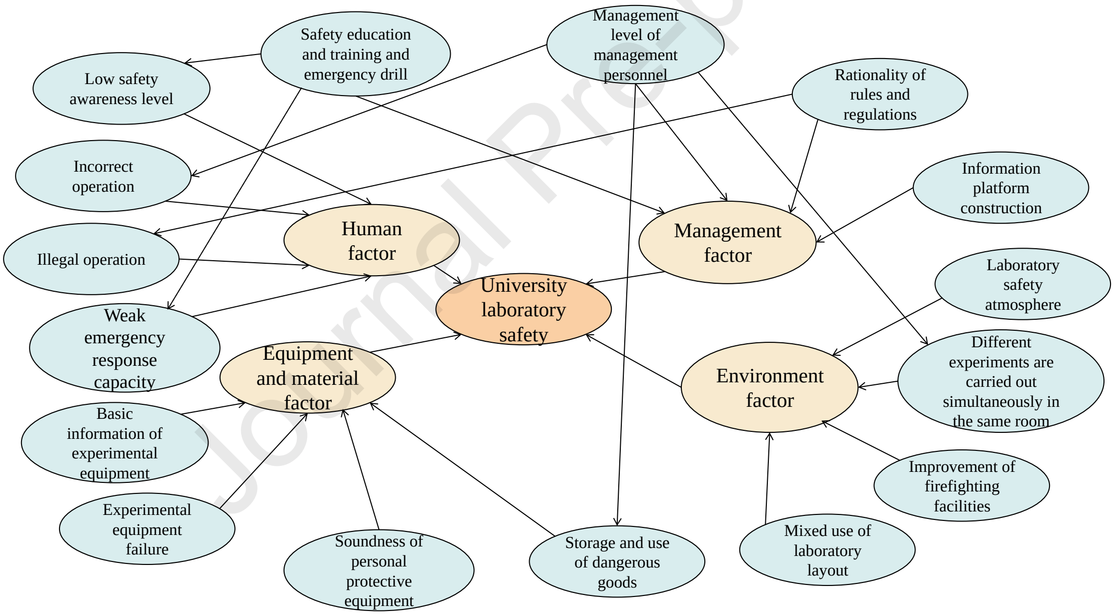

Fig.3. BN of university laboratory safety

3.2.2. The probability of risk factors

The prior probability of parent node was determined from the questionnaire results. As shown in Fig. 3, some of the risk factors depend on the state of their parent nodes. This was taken into consideration when calculating their probability. Taking “low safety awareness level” as an example, it depends on “Safety education and training and emergency drill”, for which there are four options, “Frequently”, “Occasionally”, “Rarely” and “Never”, with respective probabilities of 0.369, 0.337, 0.23 and 0.064.

We firstly calculated the percentage of the number of responses with "Yes" to "Low safety level awareness" under the option "Frequently", equal to 0.071. The conditional probabilities under other options can be calculated similarly and the final conditional probabilities of the risk factor "Low safety level awareness" on the parent node "Safety education and training and emergency drill" are shown in Table 4.

Table 4. Conditional probabilities of the risk factor "Low safety level awareness" on the parent node "Safety education and training and emergency drill"

		Safety education and training and emergency drill			
		Frequently	Occasionally	Rarely	Never
Low safety level awareness	Yes	0.071	0.129	0.226	0.379
	No	0.929	0.871	0.774	0.621

The overall probability of the option "Yes" under "Low safety level awareness" were then found as $P = 0.369 \times 0.071 + 0.337 \times 0.129 + 0.23 \times 0.226 + 0.064 \times 0.379 = 0.146$. The probabilities of different states for all risk factors are shown in Table 5.

Table 5. The probabilities of different states for each risk factor

Risk Factor	State	Prior probability
Low safety awareness level (R_{11})	Yes	0.146
	No	0.854
Incorrect operation (R_{12})	Frequently	0.064
	Occasionally	0.426
	Rarely	0.395
	Never	0.115
Illegal operation (R_{13})	Frequently	0.010
	Occasionally	0.347
	Never	0.643
Weak emergency response capacity (R_{14})	Yes	0.344

	No	0.656
Basic information of experimental equipment (R_{21})	Good	0.737
	Poor	0.263
Experimental equipment failure (R_{22})	Frequently	0.059
	Occasionally	0.231
	Rarely	0.480
	Never	0.230
Soundness of personal protective equipment (R_{23})	Good	0.884
	Poor	0.116
Storage and use of dangerous goods (R_{24})	Good	0.679
	Poor	0.321
Mixed use of laboratory layout (R_{31})	Frequently	0.082
	Occasionally	0.375
	Never	0.543
Improvement of firefighting facilities (R_{32})	Good	0.768
	Poor	0.232
Different experiments are carried out simultaneously in the same room (R_{33})	Frequently	0.188
	Occasionally	0.273
	Rarely	0.178
	Never	0.361
Laboratory safety atmosphere (R_{34})	Perfect	0.220
	General	0.684
	Poor	0.096
Information platform construction (R_{41})	Good	0.645
	Poor	0.355
Rationality of rules and regulations (R_{42})	Unreasonable	0.358
	Reasonable	0.642
Management level of management personnel (R_{43})	Tight	0.623
	General	0.250

	Loose	0.127
Safety education and training and emergency drill (R_{44})	Frequently	0.369
	Occasionally	0.337
	Rarely	0.230
	Never	0.064

It can be seen in Table 5 that half of the participants chose "Frequently" and "Occasionally" for incorrect operation, which was attributed mainly to a lack of proper supervision. For equipment and material, more than 70% of equipment experienced problems during the experiments, showing that equipment failure is frequent, resulting from either non-standardized customization of equipment or a lack of clear technical standards. For environment, irrational laboratory layout is prominent, which is specifically reflected in the fact that in about 50% of university laboratories offices are mixed with laboratories. Another common phenomenon is that different experiments are carried out simultaneously in the same space. This can be attributed to a significant increase of graduate students and limited laboratory space. The fact that laboratories are often used as offices could lead to risk accumulation with the potential to cause a chain of accidents. For management, results showed that in nearly 30% universities, the safety training and drills are usually held 1-2 times every year, far below the demand for training. This inevitably results in low experimental skills and a lack of effective emergency response in accidents.

Fig. 4 shows the different ways how the participants acquired their experiment skills: 52.70% by systematic learning whereas 39.05% with the help of senior students. Even though safety training has been carried out, the training intensity and scope are insufficient. This is mainly because that regulations for laboratories in Chinese universities haven't been improved to meet the demand of graduate students, and few universities directly include laboratory safety as a compulsory course, resulting in graduate students' low experimental skills.

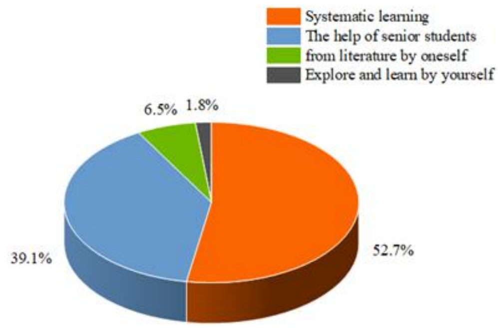

Fig.4. The questionnaire results about the way of acquiring the laboratory experiment skills for graduate students

Fig. 5 shows the frequency of regular inspection by full-time management personnel during experiment. Only just over half the participants said that the laboratory situation was inspected regularly. The main reason is that the number of full-time laboratory management personnel is insufficient in Chinese universities. Based on the website survey and telephone interview, it was found that the number of full-time management personnel is mostly two, which could not meet the demand of regular inspection. Another challenge is that most of experiments in university laboratories are exploratory with unknown dangers, which adds additional workload and uncertainties for inspection personnel.

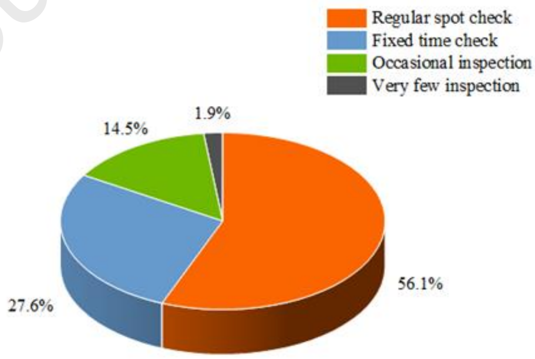

Fig.5. The questionnaire results about frequency of regular inspection by full-time management personnel during experiment

3.2.3. Conditional probability of four key factors

To determine the conditional probability, five experts in the field of safety were invited to evaluate the conditional probability of four key factors, including human, equipment and material, environment, management. The expert information and the weight of each expert, calculated from Eqs. (5) and (6) based on their job position, education level and years of work, are shown in Table 6. The fuzzy linguistic description was provided to the experts for selection, which was then transformed into the conditional probability values based on Table 2. In order to describe the detail process, "*Low safety awareness level is Yes*" is selected as an example and the whole process is shown in Table 7.

Table 6. Expert information and weight

Number	Job position	Education level	Years of work	Weight
1	Professor	PhD	25 years	0.259
2	Professor	PhD	20 years	0.241
3	Associate professor	PhD	18 years	0.222
4	Engineer	Master	11 years	0.167
5	Technician	Bachelor	8 years	0.111

Table 7. An example of determining conditional probability value for the case with "Low safety awareness level is Yes"

Bayesian nodes				Expert judgment										Fuzzy value(A')		Defuzzication value(P_j)	
R_{11}	R_{12}	R_{13}	R_{14}	Unsafe					Safe					Unsafe	Safe	Unsafe	Safe
Yes	Frequently	Frequently	Yes	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Frequently	Frequently	No	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Frequently	Occasionally	Yes	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Frequently	Occasionally	No	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Frequently	Never	Yes	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Frequently	Never	No	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Occasionally	Frequently	Yes	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Occasionally	Frequently	No	VH	VH	VH	VH	VH	VL	VL	VL	VL	VL	0.9	0.1	0.900	0.100
Yes	Occasionally	Occasionally	Yes	H	H	H	H	H	M	M	M	M	M	0.7	0.5	0.583	0.417
Yes	Occasionally	Occasionally	No	H	H	H	H	H	L	M	M	L	L	0.7	0.3926	0.641	0.359
Yes	Occasionally	Never	Yes	M	M	L	L	L	H	H	H	H	H	0.4	0.7	0.364	0.636
Yes	Occasionally	Never	No	M	M	M	L	L	H	H	M	M	H	0.4444	0.6222	0.417	0.583
Yes	Rarely	Frequently	Yes	VH	VH	VH	VH	VH	M	M	M	M	M	0.9	0.5	0.643	0.357
Yes	Rarely	Frequently	No	VH	VH	VH	VH	VH	M	L	M	L	L	0.9	0.3962	0.694	0.306
Yes	Rarely	Occasionally	Yes	M	M	L	L	L	H	H	H	H	H	0.4	0.7	0.364	0.636
Yes	Rarely	Occasionally	No	M	M	L	L	L	H	M	H	H	H	0.4	0.6518	0.380	0.620
Yes	Rarely	Never	Yes	VL	VL	VL	VL	VL	VH	VH	VH	VH	H	0.1	0.8778	0.102	0.898
Yes	Rarely	Never	No	L	L	L	L	L	H	H	M	H	H	0.3	0.6556	0.314	0.686
Yes	Never	Frequently	Yes	VH	VH	VH	VH	VH	L	L	L	L	L	0.9	0.3	0.750	0.250

Yes	Never	Frequently	No	VH	VH	VH	VH	VH	L	L	L	L	L	0.9	0.3	0.750	0.250
Yes	Never	Occasionally	Yes	M	M	L	L	L	H	H	H	H	H	0.4	0.7	0.364	0.636
Yes	Never	Occasionally	No	M	M	M	M	M	H	M	H	M	M	0.5	0.5962	0.456	0.544
Yes	Never	Never	Yes	VL	VL	VL	VL	VL	VH	VH	VH	VH	VH	0.1	0.9	0.100	0.900
Yes	Never	Never	No	VL	VL	VL	VL	VL	VH	VH	VH	VH	VH	0.1	0.9	0.100	0.900

In the BN analysis, prior probabilities are viewed as the probabilities of parent nodes, and conditional probabilities as the ones of intermediate nodes and the target node (University laboratory safety). Based on interrelation of the different nodes and their probabilities, GeNIe (University of Pittsburgh Decision systems laboratory, 2022) was used to establish the final BN for university laboratory safety in China as shown in Fig. 6.

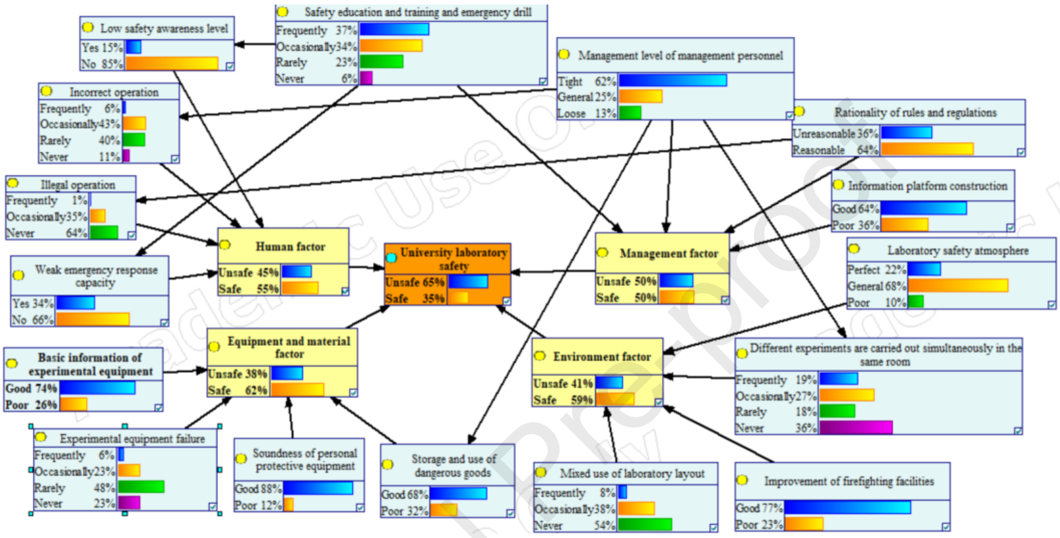

Fig.6. The final Bayesian network for university laboratory safety in China

The probability of the unsafe state for Chinese university laboratory is 65.2%, which is even larger than that of the manufacturing industry with an adaptability probability of 43.5% (Jing et al., 2021). The main reason behind the high unsafe probability is that experiments carried out in university laboratory are often exploratory, for which there is a lack of clear regulations. The management in university laboratories could also be less strict than that in the manufacturing industry.

3.3. BN analysis

3.3.1. Causal and inferential analysis

To further understand the relative importance of the influencing factors, causal and inferential analysis of these factors were conducted using GeNIe. Figs. 7 and 8 show the obtained influencing values of four key factors and sixteen risk factors respectively.

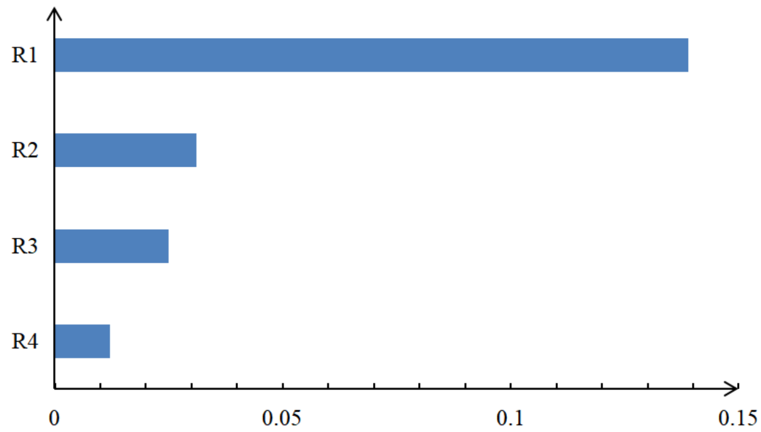

Fig.7. The influencing values of four key factors leading to university laboratory unsafe state

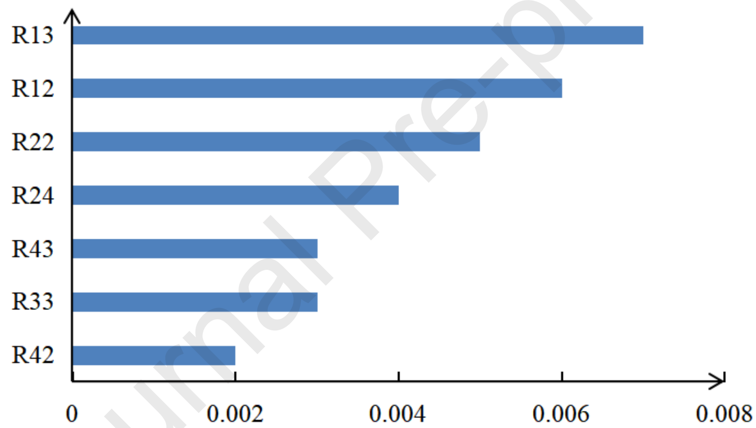

Fig.8. The key influencing values of sixteen risk factors leading to university laboratory unsafe state

For the four key factors, the human factor has the greatest influence value (0.139), which could be attributed to the low safety awareness and ability of the participants, even though they are often the ones who conduct the experiments. For the sixteen risk factors, the influence of the incorrect operation (R_{12}) and the illegal operation(R_{13}) are largest in the human factor, which is due to mainly the fact that most participants when conducting research experiments rely on the help of senior students and there is also a lack of systematic training (Lang &Yang, 2018). For equipment and material, experimental equipment failure (R_{22}) has the greatest influence (0.005), which is consistent with the questionnaire results. Apart from the equipment quality, the maintenance of equipment by a professional is also an issue because of the lack of full-time management personnel. For environment, the fact that different experiments are carried out simultaneously in the same room (R_{33}) has the largest influence value (0.003). This clearly indicates problems in the design and construction of the laboratory. For management, management level of management personnel (R_{43}) has the largest influence (0.003), because the management level of management personnel is an effective tool to prevent accidents and improve the university safety level (Staehle et al., 2016).

Assuming that the safety state of the university laboratory was 100% unsafe, the posterior probability of each influencing factor could be obtained by reverse calculations, as shown in Fig. 9. The unsafe state probabilities of management and human factors increase to nearly 60%. The probability of the unsafe human factor increases mostly from 45% to 60%, which verifies again that it has the greatest influence on university laboratory safety. By analysing the variation of 16 parent nodes, it is found that there is a prominent increase of the unsafe probability of incorrect operation, experiment equipment failure, multiple experiments conducted simultaneously in the same room, and management level of management personnel, which is consistent with the findings in Fig. 8.

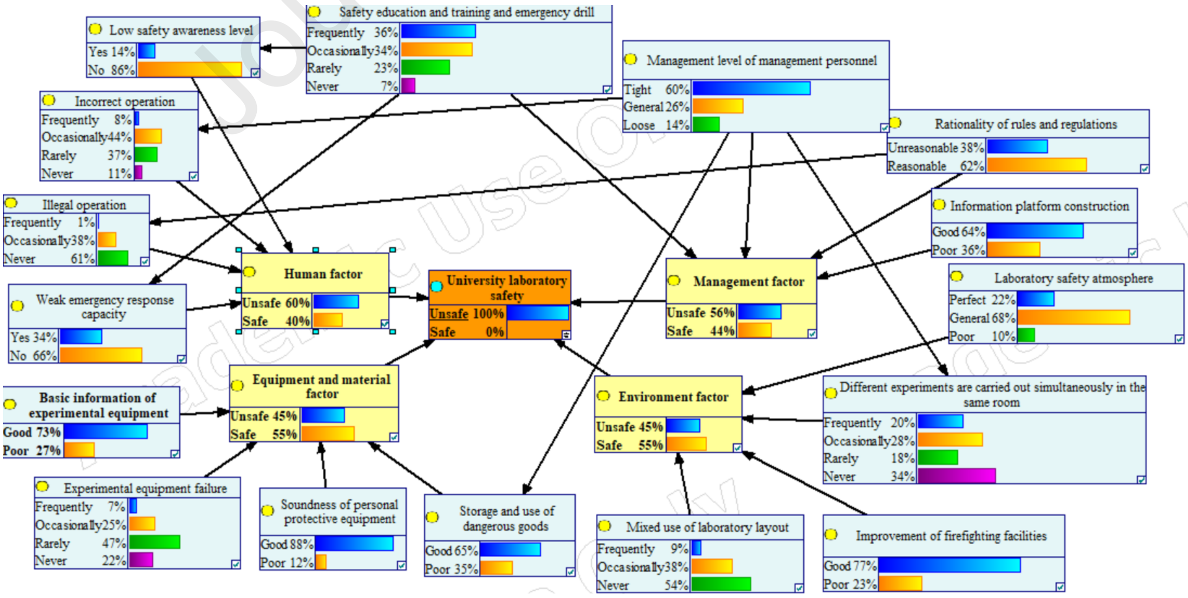

Fig.9. Posterior probability after setting university laboratory safety to 100% unsafe

3.3.2. Sensitivity analysis

With the "university laboratory safety" set as the target node, sensitivity analysis was conducted using GeNIe to analyse the variations of parent nodes. The sensitivity value of each node is shown in Fig. 10. It can be seen that R_{22} has the largest sensitivity value, followed by R_{12} and R_{13}. The results indicate that experimental equipment failure has a considerable impact, as confirmed by the questionnaire results that about 30% of experimental equipment malfunctioned relatively frequently, due to the lack of and/or irresponsible management by laboratory personnel. Moreover, laboratory personnel operation has the largest influence on university laboratory safety, as illegal and incorrect operation are often observed. This finding is consistent with the questionnaire results, in which 34.99% of the graduate students considered the operational procedures unreasonable, 2.27% failed to carry out the experiment according to operating procedures, and nearly 40% relied on senior students to obtain relevant experimental skills.

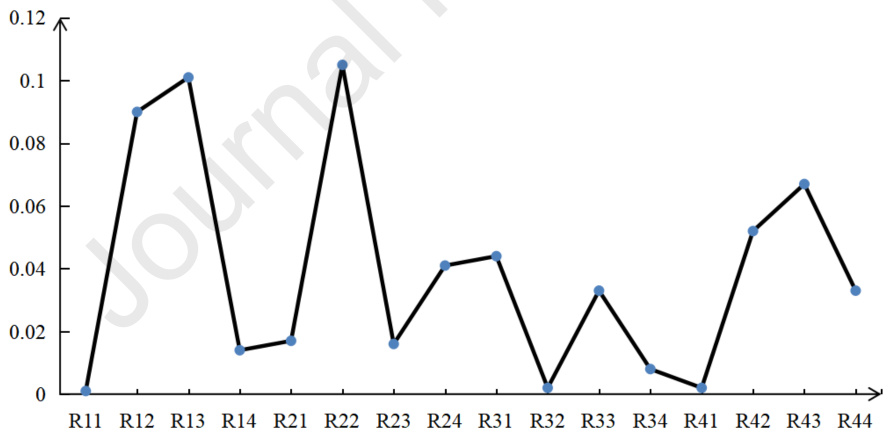

Fig.10. Sensitivity analysis of the parent nodes

4. Conclusion and Suggestions

This study presents a risk assessment model for university laboratories using questionnaire and Bayesian network (BN) analysis. The questionnaire was designed to collect information on current situations of Chinese university laboratories and the perception of graduate students on four key aspects including human, equipment and material, environment, and management. The questionnaire results were used to determine the probability of sixteen influencing factors, in which the university accident data were implicitly included as the questions were focused on the practical experience of these graduates. To acquire the overall unsafe situation across all university laboratories, the accident data was not used separately because it needs to be continuously updated and closely monitored. The conditional probability of four key aspects was calculated by combining a fuzzy triangular theory and expert judgment. Causal, inferential and sensitivity analyses were also conducted to understand the relative importance of the influencing factors. The main conclusions of this work are:

(1) The questionnaire results indicated that (i) incorrect operation is prominent in the personnel aspect; (ii) failure of experimental equipment occurs frequently because of non-standardized customization and poor maintenance; (iii) mixed use of offices and laboratories and multiple experiments conducted simultaneously in one room are most critical in the environment factor and (iv) the lack of effective training is responsible for the unsafe laboratory state in the management aspect.

(2) The causal analysis showed that the unsafe probability of university laboratories in China is 65.2%, which is higher than that of the manufacturing industry (43.5%), in which the management factor is prominent. This is mainly because of insufficient inspection personnel and inadequate supervision of students during experiments.

(3) The inferential and sensitivity analysis showed that incorrect operation, illegal operation, experimental equipment failure are the major factors affecting university laboratory safety, which is consistent with the results from the questionnaire.

Based on the above analysis, the following corresponding countermeasures on the laboratory safety management in China are proposed.

(1) Operating procedures for specific scientific research experiments should be formulated clearly and relevant graduate students should be invited to participate in its formulation to ensure the practicality of the procedures.

(2) Compulsory training courses especially for the emergence response should be conducted before all new experiments. In doing so, the dependence on the

help and guidance from senior students can be reduced, and thus the operation ability of students can be strengthened.

(3) The whole life cycle management of the experimental equipment should be in place. It is suggested that there should be a specific fund from the laboratory or the supervisor for regular check and maintenance of the experimental equipment.

(4) It is essential to build or reconfigure laboratories with access control, so only relevant people are permitted into the laboratory. Risk assessment for all experiments should be conducted and any experiment flagged with a high risk must be conducted under close supervision. Conducting of multiple experiments simultaneously in the same space should be strictly prohibited.

(5) The number of full-time management personnel for laboratories is expected to be increased to meet the demand of regular safety supervision. At the same time, management personnel should focus on the whole life cycle management of the storage, use and replacement of dangerous goods. Moreover, the management personnel need to be evaluated regularly and their communications with counterparts at other universities should be encouraged and strengthened to improve their professional level.

Credit author statement

Jinlong Zhao: Conceptualization, Methodology, Supervision, Formal analysis, Funding acquisition, Visualization, Writing – Original draft. **Huaying Cui:** Data curation, Formal analysis, Investigation, Resources, Writing – Original draft. **Guru Wang:** Visualization, Writing – review & editing. **Jianping Zhang:** Supervision, Writing – review & editing. **Rui Yang:** Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights

- An online survey with 760 university graduate students on laboratory safety in China
- Questionnaire results used to determine prior probability of safe/unsafe conditions
- Conditional probability calculated based on fuzzy triangular theory and expert judgment
- A Bayesian network analysis conducted to assess the safety level of laboratory safety
- Sensitive and inferential analysis to identify the key factors for safe management and operation of laboratories

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: