

Assessing Knowledge, Attitudes, and Risk Perceptions of Laboratory Safety Among Biomedical Engineering Students: A Case Study*

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Laboratory safety is a critical component of biomedical engineering (BME) education due to the interdisciplinary nature of the field and the associated chemical and electrical hazards. Despite its importance, limited data exist on the safety awareness of BME students in Saudi Arabia. To evaluate the knowledge, attitudes, and cognitive risk perceptions of undergraduate BME students regarding laboratory safety. A cross-sectional study was conducted among 129 undergraduate BME students from various Saudi universities using a 39-item questionnaire that covered demographics, safety knowledge, attitudes, and risk perception. Data were analyzed using nonparametric tests due to non-normal distribution. The mean knowledge score was 8.4 ± 2.4 (out of 12), with 65.1% demonstrating high knowledge levels. Knowledge significantly increased with academic level, while gender, training, and access to safety manuals showed no effect. Attitudes toward safety were mainly positive (25.0 ± 4.0 out of 35); however, concerns were raised about the availability of personal protective equipment and insufficiently emphasized safety policies. Risk perception was context-dependent: students perceived significantly higher risk in non-compliance scenarios (19.4 ± 4.0 out of 25) compared to compliant ones (12.4 ± 3.5 out of 25). Although students exhibited satisfactory knowledge and attitudes, critical gaps remain in chemical hazard awareness and emergency preparedness. Integrating structured, hands-on safety training into biomedical engineering curricula is crucial for advancing practical readiness and fostering a sustainable safety culture among students and academic institutions.

Keywords: biomedical engineering education; laboratory safety; sustainable laboratory practices; risk perception; safety culture; sustainable development in higher education

1. Introduction

Laboratories in academic institutions play a crucial role in the educational process by providing students with essential hands-on experience in their chosen fields. However, laboratories pose inherent risks as students are often exposed to chemical, physical, and biological hazards [1, 2]. Given these risks, effective safety protocols are essential to prevent serious injuries, fatalities, and long-term health hazards [3, 4]. Consequently, universities must prioritize student safety education to ensure that they are equipped with the knowledge and skills required to safely navigate these risks [5–7]. According to the U.S. Occupational Safety and Health Administration (OSHA), laboratory accidents cause thousands of injuries annually, with the most common being chemical burns, electrical burns, and eye injuries due to exposure to hazardous substances [8]. Between 2008 and 2018, 11

fatalities were reported in academic laboratories worldwide, resulting from incidents such as explosions, chemical exposure, and equipment-related accidents, highlighting the critical need for improved safety protocols and training [3]. Moreover, in the United States alone, 126 chemical-related incidents were reported in laboratories at educational and research institutions, including universities, according to the U.S. Chemical Safety and Hazard Investigation Board between 2001 and 2018 [9].

Several studies have examined laboratory safety awareness among university students, consistently revealing gaps between theoretical understanding and practical application, regardless of national context or program maturity. A cross-sectional study conducted at three Trinidadian tertiary institutions found that students had a relatively high awareness of chemical laboratory safety, particularly in hazard identification and emergency response; however, they demonstrated weaknesses in safety practices and attitudes. The study recommended the integration of enhanced safety training

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and curriculum reforms to improve compliance and reduce accidents [10]. Similarly, a pilot study in Hong Kong, involving 91 laboratory workers, found strong general awareness but notable deficiencies in hazard recognition and emergency response skills, indicating a need for a more robust safety culture in academic institutions [11]. In contrast, other studies have reported generally low levels of safety awareness. For instance, a cross-sectional study of 335 students at Kunming University of Science and Technology revealed that over 63% had inadequate laboratory safety awareness, highlighting the importance of mandatory safety education [12]. Such an observation was supported by research involving 361 undergraduate students in Malaysia, which revealed that safety knowledge and motivation significantly influenced safety behavior, with safety commitment acting as a key mediating factor [13]. However, even when safety education is present, incidents remain prevalent. A 2024 study of PhD students in chemical and pharmaceutical sciences at the University of North Carolina at Chapel Hill found that while 81% had been trained in the use of Safety Data Sheets during their undergraduate studies, 20% had experienced a laboratory injury, and 40% had witnessed near misses – with nearly 40% of those injuries going unreported [14]. These findings highlight ongoing global challenges in ensuring sustainable laboratory safety practices in educational settings and underscore the urgent need for structured training and a more proactive, embedded safety culture.

In Saudi Arabia, the expansion of higher education, particularly in the fields of science and engineering, has led to a growing emphasis on laboratory-based learning [15]. As universities increasingly invest in advanced research facilities, it is crucial to address the need for effective safety training and protocols. For instance, a study examined laboratory safety and awareness among clinical laboratory students and staff in Saudi Arabia, revealing that students generally have lower knowledge of safety protocols compared to university staff. It emphasizes the necessity of integrating safety education into academic curricula to enhance awareness and adherence to safety measures in laboratory environments [16]. Another cross-sectional study conducted at Taif University in Saudi Arabia revealed that while laboratory workers exhibited strong safety awareness, undergraduate medical science students showed significant gaps, especially in emergency procedures and safety practices, further emphasizing the need for enhanced institutional safety education and training [17].

Biomedical engineering (BME) programs inherently pose complex laboratory safety challenges due

to their interdisciplinary structure, which combines concepts from biology, medicine, and engineering [18]. This integration requires students to engage with advanced technological equipment and manage potentially hazardous biological and chemical materials, thereby underscoring the critical need for comprehensive and specialized safety education tailored to the field's unique demands [18, 19]. BME students frequently encounter chemical, biological, electrical, and mechanical hazards, highlighting the need to assess their safety awareness and preparedness.

In Saudi Arabia, the field of BME has been expanding steadily, with undergraduate programs increasingly offered at universities across the country. New programs continue to emerge in response to national development goals and the growing demand for skilled biomedical professionals in the healthcare and technology sectors. This trend aligns with the strategic objectives of Saudi Vision 2030, which emphasizes innovation, workforce localization, and advancements in the health system [20]. As of 2024, more than 10 universities across the country offer BME undergraduate programs, with most of these programs concentrated in the central region. These programs typically span five years and include integrated coursework in bioinstrumentation, biomechanics, biomaterials, and medical imaging. Laboratory components are embedded throughout the curriculum, often involving electrical circuits, hazardous chemicals, and biological specimens. Hence, evaluating the students' readiness and safety awareness is essential to support the quality and sustainability of these academic programs as they continue to evolve. This aligns with global sustainability goals by fostering safe, inclusive, and resilient educational institutions [21–23]. Despite its foundational role in sustainable academic environments, laboratory safety has received limited attention in the context of interdisciplinary undergraduate education, particularly within Saudi Arabia's emerging BME programs. While laboratory safety has been explored in medical [17, 24, 25] and industrial [26] settings, there remains a lack of focused research on undergraduate BME students in Saudi Arabia.

Internationally, laboratory safety training for biomedical and chemical laboratory environments is guided by well-established frameworks issued by the World Health Organization (WHO) [27] and OSHA [28]. The WHO Laboratory Biosafety Manual outlines essential competencies for work in biomedical laboratories, including structured risk assessment, recognition of biological and chemical hazards, appropriate use of personal protective equipment, containment strategies, waste management, decontamination procedures, and

clearly defined emergency responses [27]. Similarly, OSHA's Laboratory Safety Guidance emphasizes hazard communication, Safety Data Sheet literacy, safe handling and storage of chemicals, electrical and equipment safety, and the implementation of standardized fire and emergency protocols [28]. Collectively, these guidelines constitute internationally accepted standards for laboratory-safety education. Establishing this global context provides a foundation for evaluating current laboratory safety training practices in BME programs.

This cross-sectional study addresses that gap by assessing safety knowledge, attitudes, and risk perception, providing a comprehensive perspective to inform curriculum development and institutional policies. In alignment with the objectives of Saudi Vision 2030, the study also supports the development of targeted interventions to better prepare students for the demands of modern laboratory environments. Based on this rationale, the study proposes the following hypotheses: (1) that BME students demonstrate a moderate level of knowledge regarding laboratory safety protocols; (2) that students generally exhibit positive attitudes toward safe laboratory practices; and (3) students' risk perceptions may vary based on their prior safety training and laboratory exposure.

2. Materials and Methods

A cross-sectional study was conducted using a structured questionnaire consisting of two components: a developed section aimed at evaluating knowledge and attitudes toward safety practices in undergraduate BME laboratories in Saudi Arabia, and a risk perception items section based on a previously used instrument that assessed cognitive perceptions of laboratory risks and compliance with safety protocols in university laboratory environments [19].

A cross-sectional survey design was chosen for its suitability in efficiently collecting self-reported data from a geographically dispersed student population. This method is particularly suitable for exploratory research that focuses on behavioral awareness and safety perceptions in academic settings.

2.1 Data Collection

Data were collected using a web-based questionnaire administered via Google Forms, which assessed the knowledge, attitudes, and perceptions of laboratory risks among BME students. The questionnaire was distributed through BME student networks via WhatsApp and email to undergraduate students across Saudi Arabia. A total of 129 students participated in the study, representing

universities across Saudi Arabia. The majority were from institutions in the central region, where most BME programs are located (7 universities). A smaller proportion of participants were enrolled in universities in the eastern (3 universities) and western regions (1 university), reflecting the national distribution of BME programs at the time of the study. Ethical approval was obtained from King Saud University's Institutional Review Board (reference number E-23-7768), and informed consent was obtained from all participants before data collection.

2.2 Questionnaire Characteristics

The questionnaire consisted of 39 items divided into four sections: general and demographic information (10 items), basic knowledge (12 items), attitudes (7 items), and risk perception (10 items). The demographic section gathered data on participants' age, gender, academic level, program type, number of laboratory sessions attended per week, and geographic region. Additional questions assessed whether participants believed they had adequate knowledge of laboratory safety and hazards, whether they had attended a laboratory safety workshop at their academic institution, and whether a safety manual was available to all students at their institution. For respondents who indicated attending such workshops, follow-up questions were asked regarding the type of training received and whether it included content on electrical safety and hazards.

The knowledge section comprised 12 items covering key areas, including electrical safety (items 1–8), chemical handling (items 9–10), and general laboratory hazard awareness (items 11–12). While most were standard true/false items, two questions asked students if they knew where the emergency equipment was located and how to use it. These were included to capture a more comprehensive understanding of their practical readiness in laboratory settings. The items were designed to reflect widely recognized safety practices.

The attitude section included seven items that evaluated students' attitudes toward the safety culture within their academic environment. Specifically, the items explored students' views on the importance of safety training, adequacy of protective equipment, confidence in laboratory supervisors' knowledge, and the institution's responsibility in communicating risks. Additionally, the items assessed students' comfort in raising safety concerns and their overall sense of safety in the laboratory. This section aimed to capture students' general attitudes regarding how safety is prioritized and managed within their educational setting.

The risk perception section comprised 10 items to assess students' cognitive risk perception of potential harm in the laboratory under two distinct conditions: when safety procedures are followed and when they are not. Each question was framed in paired statements to reflect both compliance and non-compliance scenarios, a methodological choice that emphasizes the importance of conditional framing in evaluating risk perception and its relation to safety behavior [19]. Total scores for compliance- and non-compliance-framed items were calculated and compared across demographic and experiential variables, including gender, academic level, prior safety training, and access to institutional safety resources, to explore patterns in how students perceive risk in laboratory settings.

2.3 Questionnaire Validation

To establish content validity, three independent experts with doctoral degrees reviewed the questionnaire. Selection criteria included four years of academic research experience. Experts received guidelines outlining the study's purpose, questionnaire structure (knowledge, attitude, and risk perception domains), and evaluation criteria. Items were rated for relevance and clarity on a four-point scale (1 = low, 4 = high). Expert feedback refined the wording of items and enhanced face validity. For quantitative assessment, ratings were dichotomized: scores 1-2 were assigned a value of 0 ("not relevant"), and scores 3-4 were assigned a value of 1 ("relevant"). The scale-level content validity index (S-CVI/Avg) was computed using the average method, with a value of 1.0 considered acceptable for three to five reviewers [29]. The finalized instrument achieved an S-CVI/Avg of 1.0 for relevance and clarity, indicating acceptable validity [29].

2.4 Data Analysis

Data were analyzed using IBM SPSS Statistics version 30. For the knowledge domain, a binary scoring system was implemented, awarding one point for each correct answer and zero points for incorrect or unclear responses. The total scores ranged from 0 to 12 and were categorized into three levels: low (0-4), moderate (5-8), and high (9-12).

The attitude and risk perception items were assessed using a five-point Likert scale, where 5 indicated "strongly agree" and 1 indicated "strongly disagree." The total attitude score ranged from 1 to 35, with negatively worded items reverse-scored to ensure consistency. Items 1-4, 6, and 7 were positively framed, and item 5 was negatively framed. Attitude scores were classified

into two groups: negative, 1-17 points, and positive, 18-35 points.

For the risk perception section, total scores for compliance- and non-compliance-framed items were calculated, with a range of 1-25 for both types of items. The scores were then compared across demographic variables, including gender, academic level, prior safety training, and access to institutional safety resources, to explore patterns in students' perceptions of risk in laboratory settings.

Descriptive statistics, including means, standard deviations (SD), and frequencies, were used to summarize participant demographics and response patterns. The distribution of continuous variables, such as knowledge, attitude, and risk perception scores, was assessed using the Shapiro-Wilk test. As the normality assumptions were violated ($p < 0.05$), nonparametric statistical tests were conducted.

The Kruskal-Wallis test was used for comparisons across variables with more than two groups, such as academic level and geographical region. For pairwise comparisons, the Mann-Whitney U test was used to explore differences in knowledge, attitudes, and risk perception based on binary factors, including gender, access to safety manuals, and attendance at safety training workshops. Spearman's rank correlation was used to evaluate the relationship between academic level and participants' knowledge, perception, and attitude scores. A p -value of < 0.05 was considered statistically significant, and all results are presented as mean \pm SD.

3. Results

3.1 Participant Characteristics

The questionnaire was completed by 129 undergraduate students, including 64 females (49.6%) and 65 males (50.4%), with a mean age of 21.2 ± 2.5 years. Regarding academic level, 15.5% of participants were freshmen, 22.5% were sophomores, 17.0% were juniors, 31.0% were seniors, and 14.0% were interns. Most respondents were from the central region (84.5%), followed by the eastern region (14.7%) and the western region (0.8%). This regional distribution reflects the geographic availability of BME programs in Saudi Arabia, which are largely concentrated in the central region, with limited offerings in the eastern and western regions. Moreover, 96.9% of the respondents were enrolled in a Bachelor of Science program, while only 3.1% were attending an Associate program. Most participants reported attending 1-2 laboratory sessions (54.3%), while 36.4% attended 3-4 laboratory sessions, and 9.3% had more than four laboratory sessions per week. Additionally, 74.4% of the participants reported having sufficient

knowledge of basic safety and hazards in the college laboratory environment.

The majority of respondents (64.3%) reported that their academic institution did not have an accessible laboratory safety manual, while 28.7% indicated that an accessible manual was available, and 7% did not know if one was available.

Furthermore, only 18.6% of the participating students indicated that their academic institutions provided specialized workshops on laboratory safety and hazards, while 81.4% reported not having received such training. Among the students who attended safety training workshops, 63.6% received general safety training, 25.0% attended sessions focused on electrical hazards, 6.8% were trained on biohazards, and 4.6% received training specific to chemical hazards. The majority of respondents (88.6%) indicated that their safety training included content on electrical safety and hazards, whereas only a small proportion (11.4%) reported that this topic was not covered. A detailed breakdown of the demographic data is presented in Appendix A.

3.2 Assessment of Knowledge

The results of the knowledge section are summarized in Table 1. The knowledge assessment results revealed that most BME students exhibited a good understanding of basic laboratory safety principles. The average knowledge score was 8.4 ± 2.4 SD, with 87.6% of the participating students scoring above half of the maximum possible score. In sum, 4.7% of participants had low knowledge levels, 30.2% had moderate knowledge levels, and 65.1% exhibited high knowledge levels.

Most students identified that electrical shocks could lead to severe outcomes, such as burns, paralysis, and death (94.6%), and acknowledged the importance of avoiding contact with electrical circuits using wet hands or materials (92.3%). A large proportion of respondents also understood that electrical device maintenance should only be performed after switching off the main power (76%) and were aware of the function of circuit protection devices (76.8%).

However, only 53.5% of the participants correctly identified the primary function of a chemical fume hood, and half (52.7%) were aware that lithium-ion batteries should not be disposed of in general waste bins. Additionally, 60.5% of students reported knowing the location of emergency safety equipment (eyewash unit, safety showers, fire extinguisher, fire blanket, first aid kit), whereas only 36.4% reported knowing how to use them effectively.

The average knowledge scores were 7.1 ± 1.8 for freshman students, 7.0 ± 2.4 for sophomore students, 7.2 ± 2.2 for junior-level students, 9.6 ± 2.1

for senior-level students, and 9.8 ± 2.2 for students completing their internship. Knowledge scores were compared across academic levels (freshman, sophomore, junior, senior, and intern) to assess their impact on the participants' basic safety knowledge. A significant difference was found among the groups based on their academic level (Kruskal–Wallis test: $p < 0.001$). Post hoc analysis revealed that the participants in their senior year had significantly higher basic knowledge of safety in laboratory compared with those in their freshman (Mann–Whitney U test: $Z = -3.3$, $p = 0.01$), sophomore (Mann–Whitney U test: $Z = -3.7$, $p < 0.01$), those in junior year (Mann–Whitney U test: $Z = -3.7$, $p < 0.001$). Similarly, participants in their internship year had significantly better basic knowledge compared with those in their freshman (Mann–Whitney U test: $Z = -3.2$, $p = 0.001$), sophomore (Mann–Whitney U test: $Z = -3.4$, $p < 0.001$), those in junior year (Mann–Whitney U test: $Z = -3.5$, $p < 0.001$). However, no significant differences were observed between seniors and interns or between freshmen and junior-level students.

Moreover, students who self-reported having sufficient knowledge of basic laboratory safety and hazards scored significantly higher than those who indicated that they did not have sufficient knowledge (Mann–Whitney U test: $Z = -3.6$, $p < 0.001$). In contrast, gender, region, attending safety workshops, and accessibility to a safety manual did not significantly affect knowledge scores. Additionally, a positive correlation was found between the knowledge score and academic level (Spearman's correlation: $r_s = 0.4$, $p < 0.001$, $n = 129$).

3.3 Assessment of Students' Attitude Toward Safety in Laboratory

The questionnaire items that assess students' attitudes toward laboratory safety, along with their response rates, are detailed in Table 2. A majority of students (79.8%) indicated that providing laboratory safety training is essential for all students. Additionally, 63.5% believed that their laboratory supervisors have sufficient knowledge of safety procedures and associated risks.

Attitudes toward the availability of safety equipment were more moderate, with only 31.8% of respondents indicating that their department has sufficient personal protective equipment, such as gloves, laboratory coats, and safety glasses, for each student. Meanwhile, 75.9% of participants indicated that institutions should ensure that laboratory personnel explain safe practices and potential hazards before each experiment.

Furthermore, more than half (58.1%) of students reported that the safety aspects are underestimated

Table 1. Knowledge Assessment

Item	Frequency (%)		Mean \pm SD
	Correct	Incorrect	
The human body is a poor conductor of electricity. (F)	88 (68.2)	41 (31.8)	0.7 \pm 0.5
It is safe to work on electrical circuits in the laboratory with bare hands. (F)	97 (75.2)	32 (24.8)	0.8 \pm 0.4
Electrical shocks can cause skin and internal tissue burns, paralysis, and death. (T)	122 (94.6)	7 (5.4)	1 \pm 0.2
Electrical device maintenance should be carried out after switching off the main power. (T)	98 (76.0)	31 (24.0)	0.8 \pm 0.4
Power extensions can be used with high-voltage equipment regardless of their amperage requirements. (F)	80 (62.0)	49 (38.0)	0.6 \pm 0.5
Electrical grounding is a backup pathway that provides another route for the current to flow back to the ground if there is a fault in the wiring system. (T)	92 (71.3)	37 (28.7)	0.7 \pm 0.5
Circuit protection devices are intended to restrict or shut off the flow of electricity immediately in the case of a ground fault, overload, or short circuit in the wiring system. (T)	99 (76.7)	30 (23.3)	0.8 \pm 0.4
Contacting circuits with wet hands or materials must be avoided. (T)	119 (92.3)	10 (7.8)	0.9 \pm 0.3
A chemical fume hood's primary function is to contain and then exhaust hazardous and/or odorous chemicals to prevent the discharge of dangerous substances into the laboratory environment. (T)	69 (53.5)	60 (46.5)	0.5 \pm 0.5
Rechargeable Lithium-ion (Li-ion) batteries and devices containing these batteries can be safely disposed of in general waste bins. (F)	68 (52.7)	61 (47.3)	0.5 \pm 0.5
Do you know the location of the emergency safety equipment (eyewash unit, safety showers, fire extinguisher, fire blanket, first aid kit)? (Yes)	78 (60.5)	51 (39.5)	0.6 \pm 0.5
Do you know how to use emergency safety equipment (eyewash unit, safety showers, fire extinguisher, fire blanket, first aid kit)? (Yes)	47 (36.4)	55 (42.6)	0.6 \pm 0.5
Total Knowledge Score			8.4 \pm 2.4

Table 2. Students' attitude toward safety in laboratories

Item	Frequency (%)					Mean \pm SD
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	
I believe that providing laboratory safety training is essential for every student in Biomedical Engineering.	75 (58.1)	28 (21.7)	17 (13.2)	3 (2.3)	6 (4.6)	4.3 \pm 1.1
I believe that the laboratory supervisors have sufficient knowledge of the safety procedures and risks.	35 (27.1)	47 (36.4)	39 (30.2)	3 (2.3)	5 (3.9)	3.8 \pm 1.0
The laboratories in my department have enough protective equipment, such as gloves, laboratory coats, and safety glasses, for each student.	12 (9.3)	29 (22.5)	45 (34.9)	28 (21.7)	15 (11.6)	3.0 \pm 1.1
My academic institute must sufficiently explain the safe practices and possible hazards before each experiment.	55 (42.6)	43 (33.3)	25 (19.4)	4 (3.1)	2 (1.6)	4.1 \pm 1.0
I believe that the safety aspects in laboratories are often underestimated or undervalued.	15 (11.6)	60 (46.5)	34 (26.4)	17 (13.2)	3 (2.3)	2.5 \pm 1.0
I am comfortable discussing my safety concerns with the laboratory supervisor	30 (23.3)	41 (31.8)	41 (31.8)	11 (8.5)	6 (4.7)	3.6 \pm 1.0
In general, I feel safe in the laboratory.	35 (27.1)	49 (38.0)	33 (25.6)	8 (6.2)	4 (3.1)	3.8 \pm 1.0
Total Attitude Score						25.0 \pm 4.0

or undervalued in laboratories. Additionally, 55.1% reported being comfortable discussing safety concerns with laboratory supervisors, whereas 65.1% felt safe in their laboratory environment.

The mean attitude score was 25.0 \pm 4.0 out of 35, corresponding to 71.4%, which reflects an overall positive attitude among students toward laboratory safety within their academic institutions. Only 4.7% of respondents demonstrated a negative attitude,

whereas the vast majority (95.3%) scored above the midpoint of the total attitude scale.

A statistical analysis was conducted to investigate the variables that affect students' attitudes toward safety in academic laboratories. The findings indicated that there was no significant difference in the calculated attitude score across academic level, gender, previously attended safety workshops, region, or accessibility of safety manuals.

3.4 Cognitive Risk Perception Toward Laboratory Safety

Table 3 summarizes the frequency distributions and percentages for each item. A large proportion of participating students (72.1%) indicated that failing to follow safety procedures exposed them to danger, while 14.7% perceived risk even when following safe practices. Similarly, 70.6% of participants acknowledged the potential for serious harm when not complying with safety practices. In contrast, the perception of risk under full compliance was considerably lower (14.0%).

If exposed to risky situations, 68.2% of students agreed that such exposure is frequent if safety practices were not followed, compared to only

13.2% who indicated it would occur even when safety procedures were followed. When asked about the risk of minor injury, 58.9% reported that the risk is high without compliance, whereas only 13.2% perceived such risk under compliance. Similarly, 68.2% of students believed there was a high likelihood of injury if safety protocols were not followed, while only 14.7% endorsed this perception when compliance was maintained.

A Mann–Whitney U test revealed a statistically significant difference between students' cognitive risk perception under compliance and non-compliance conditions ($Z = -11.11$, $p < 0.001$); no significant effects were found for gender, region, safety workshop attendance, academic level, or access to a safety manual.

Table 3. Cognitive Risk Perception

Item	Frequency (%)					Mean \pm SD
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	
1-a: I am often at danger from hazardous materials or situations during the experiment if I fail to follow safety practices.	40 (31.0)	53 (41.1)	19 (14.7)	8 (6.2)	9 (7.0)	3.8 \pm 1.2
1-b: I am often at danger from hazardous materials or situations during the experiment, even if I follow safety practices.	3 (2.3)	16 (12.4)	41 (31.8)	46 (35.7)	23 (17.8)	2.5 \pm 1.0
2-a: It would be possible for me to experience serious injury or harm during the experiment if I don't comply with safety procedures.	54 (41.9)	37 (28.7)	26 (20.2)	6 (4.7)	6 (4.7)	4.0 \pm 1.1
2-b: It would be possible for me to experience a serious injury or harm during the experiment even if I comply with safety procedures.	4 (3.1)	19 (14.7)	46 (35.7)	45 (34.9)	15 (11.6)	2.6 \pm 1.0
3-a: During the experiment, I am frequently exposed to risky situations that could cause injury or harm if I am not following safety practices	44 (34.1)	44 (34.1)	26 (20.2)	11 (8.5)	4 (3.1)	3.2 \pm 0.7
3-b: During the experiment, I am frequently exposed to risky situations that could cause injury or harm even if I am following safety practices.	1 (0.8)	18 (14.0)	45 (34.9)	46 (35.7)	19 (14.7)	2.5 \pm 0.9
4-a: I am at high risk of minor injury or harm in the experimental environment if I do not comply with safety procedures.	34 (26.4)	54 (41.9)	26 (20.2)	12 (9.3)	3 (2.3)	3.8 \pm 1.0
4-b: I am at high risk of minor injury or harm in the experimental environment even if I comply with safety procedures.	3 (2.3)	17 (13.2)	42 (32.6)	46 (35.7)	21 (16.3)	2.50 \pm 1.0
5-a: There is a high likelihood that I will get injured or be harmed during the experiment if I am not following safety practices.	41 (32.0)	49 (38.0)	25 (19.4)	9 (7.0)	5 (3.9)	3.87 \pm 1.1
5-b: There is a high likelihood that I will get injured or be harmed during the experiment, even if I am following safety practices.	2 (1.6)	11 (8.5)	39 (30.2)	52 (40.3)	25 (19.4)	2.3 \pm 0.9
Total score					Compliance	12.4 \pm 3.5
					Non-compliance	19.4 \pm 4.0

a: Compliance statements.

b: Non-compliance statements.

3.5 Scale Reliability

To evaluate questionnaire consistency, Cronbach's alpha (α) was calculated for each section. The knowledge domain showed a reliability coefficient of 0.7. The attitude and risk perception domains yielded α values of 0.6 and 0.7, respectively, which were considered acceptable [31]. The overall reliability was 0.7, confirming the questionnaire as an acceptable tool for assessing students' laboratory safety knowledge, attitudes, and risk perception [31].

4. Discussion

This study aimed to evaluate the knowledge, attitudes, and perceptions of cognitive risk among BME students in Saudi Arabia regarding laboratory safety. The results indicate a generally satisfactory level of safety knowledge with a mean score of 8.4 ± 2.4 (70.0%), in which the majority of students demonstrated high awareness of electrical safety principles. However, significant knowledge gaps remain in chemical handling, waste disposal, and emergency preparedness. Importantly, only 36.4% of students reported knowing how to use emergency equipment, highlighting a disconnect between theoretical understanding and practical readiness, a pattern also observed in prior studies that attribute such gaps to limited institutional support and emergency training. [31, 32].

When evaluated against these internationally recognized biosafety standards, the safety preparation provided to BME students exhibits several notable gaps. Although students demonstrated satisfactory general knowledge, only 18.6% reported having received formal laboratory safety training. More critically, hazard-specific instruction, particularly in chemical safety (4.6%) and biohazard procedures (6.8%), was uncommon, despite these competencies being core requirements of WHO and OSHA training frameworks [27, 28]. Furthermore, only 36.4% of respondents reported knowing how to operate emergency equipment, indicating a lack of practical, competency-based instruction that is fundamental to global biosafety expectations [27]. These findings suggest opportunities to enhance laboratory-safety training in BME programs to better align with internationally recommended standards for comprehensive, practice-oriented safety education.

The self-reported data also provide insight into the nature of laboratory safety instruction currently implemented in BME programs. Students' responses indicate that, when present, training is highly variable and typically limited to general safety orientations rather than to structured, competency-driven modules. The majority of partici-

pants reported not receiving detailed or hands-on instruction in essential areas, including the use of emergency equipment, waste management, and hazard-specific procedures. Moreover, students provided inconsistent information regarding the duration, delivery format, and mandatory status of these sessions, suggesting that training practices vary substantially across institutions and lack standardization. This variability further underscores the need for coherent, comprehensive, and uniformly implemented safety training across BME curricula nationwide.

These observations are consistent with broader findings in engineering education, where structured and curriculum-integrated safety instruction has been shown to improve students' hazard awareness and the adoption of safe practices. For example, a study demonstrated that an online safety module significantly enhanced engineering students' understanding of hazard identification, risk evaluation, and procedural safety behaviors following formal training [33]. This evidence reinforces the pedagogical importance of systematic safety education in engineering disciplines and suggests that the limited and inconsistently delivered training available to BME students in Saudi Arabia may contribute to the deficiencies observed in hazard-specific knowledge and emergency preparedness.

Positive attitudes toward safety were evident, with a mean attitude score of 25.0 ± 4.0 (71.4%). Most students valued safety training and acknowledged the importance of institutional responsibility in promoting safety. However, concerns about insufficient safety equipment and undervaluation of safety culture within departments suggest an institutional gap. These findings align with [16], which reported a discrepancy between the perceived importance of safety and the resources provided to support it in Saudi Arabia.

Cognitive risk perception scores revealed an explicit behavioral dependency: students perceived significantly higher risk when safety protocols were not followed (mean = 19.4 ± 4.0 , 77.6%) compared to when they were followed (mean = 12.4 ± 3.5 , 49.6%). This supports the conditional framing approach, which highlights that individuals' perceived risk varies with context and behavioral compliance [19]. Contrary to the proposed third hypothesis, the findings did not reveal statistically significant differences in risk perception scores based on prior safety training. This suggests that students' risk perceptions may be more influenced by situational framing (i.e., compliance vs. non-compliance) than by background factors such as formal training or previous exposure. This aligns with prior research emphasizing the role of situational awareness and perceived consequences in

shaping safety behavior [19]. This behavioral sensitivity is crucial because it indicates that students understand the implications of safety violations. However, the relatively moderate concern, even under compliant conditions, may reflect uncertainty about laboratory conditions or supervisory oversight and is consistent with findings from previous studies assessing the perceptions and practices of students and workers in medical laboratories [16, 17].

Nevertheless, despite positive indicators, formal safety training remained limited, with only 18.6% of students reporting structured instruction, and fewer than 30% receiving training on specific laboratory hazards. These findings underscore the ongoing need to strengthen safety education in interdisciplinary programs such as BME. Prior studies have emphasized the importance of structured and interactive approaches to safety instruction, such as remote modules for electrical safety [34] and educational interventions that significantly improve laboratory knowledge, attitudes, and practices [35]. While understanding students' risk perception is also critical for designing effective safety education [36], integrating hands-on or simulation-based safety training into BME curricula may be key to bridging the gap between theoretical knowledge and practical application.

These observations contribute to the broader conversation on laboratory safety education, offering contextually grounded insights that may inform similar efforts in other evolving academic environments. In addition to its practical implications, this study makes a methodological contribution by introducing a structured knowledge scale focused on core laboratory safety principles. Although exploratory, this scale may serve as a foundation for the future development of validated assessment tools to evaluate safety awareness in interdisciplinary fields.

4.1 Study Limitations and Future Research Directions

This study has several limitations. First, the questionnaire was distributed electronically, which required internet access and may have limited participation from students. Additionally, the geographic representation of participants was constrained by the national distribution of BME programs at the time of the study. Most universities offering undergraduate BME programs were located in the central region (7 universities), with only a few in the eastern (3 universities) and western (1 university) regions. This uneven distribution may have introduced sampling bias, as the majority of respondents were likely drawn from central institutions. Moreover, over half of the respondents had

only 1–2 laboratory sessions per week, which may restrict the depth of insights into more advanced safety behaviors. These factors limit the generalizability of the findings beyond the sampled population and should be considered when interpreting the results.

Another limitation is the response rate. Although the study invitation was distributed to 300 students out of an estimated total of 800–1,000 BME students currently enrolled across the country, responses were obtained from only 129 participants. This limited reach may affect the representativeness of the findings and should be taken into account when interpreting conclusions about students' safety knowledge, attitudes, and risk perceptions.

Furthermore, the study focused solely on undergraduate students, excluding faculty perspectives and institutional safety policies that could offer profound insight into systemic factors influencing safety culture. Future studies should incorporate both qualitative methods and broader involvement, including laboratory supervisors and safety officers, to provide a more comprehensive understanding of safety dynamics. Additionally, longitudinal studies could assess how knowledge and attitudes develop across academic years or after formal safety interventions, providing more substantial evidence for curriculum development.

5. Conclusions

This study reveals that while BME students in Saudi Arabia generally exhibit satisfactory knowledge and positive attitudes toward laboratory safety, critical gaps remain, particularly in awareness of chemical hazards and emergency preparedness. These deficiencies highlight the need for structured, hands-on safety training and greater institutional emphasis on safety culture. Integrating comprehensive safety education into BME curricula, supported by accessible resources and practical training, is crucial for equipping students to navigate the complex risks associated with interdisciplinary laboratory environments. These efforts should align with national goals outlined in Saudi Vision 2030, ensuring that future engineers are not only technically competent and safety-conscious but also contributors to safe and sustainable academic and professional environments.

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Abbreviations

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Appendix A: Demographic characteristics of biomedical engineering students participating in the study.

Item	N (%)
Age	Mean \pm SD: 21.23 \pm 2.52 SD
Gender	
Female	64 (49.6)
Male	65 (50.4)
Academic level	
Freshman	20 (15.5)
Sophomore	29 (22.5)
Junior	22 (17.0)
Senior	40 (31.0)
Interns	18 (14.0)
Program type	
Bachelor	125 (96.9)
Associate	4 (3.1)
Number of laboratory sessions per week	
1–2	70 (54.3)
3–4	47 (36.4)
> 4	12 (9.3)
Region	
Central	109 (84.5)
Eastern	19 (14.7)
Western	1 (0.8)
Do you have sufficient knowledge of laboratory safety and hazards?	
Yes	96 (74.4)
No	33 (25.6)
Have you attended a safety and hazard training workshop at your institution?	
Yes	44 (18.6)
No	85 (81.4)
Does your academic institution have an accessible safety manual?	
Yes	37 (28.7)
No	83 (64.3)
I do not know	9 (7.0)
	(% among trained/% of total sample)
What type of safety training did you receive? (n = 44)	
General	28 (63.6/21.7)
Chemical hazards	2 (4.6/1.6)
Electrical hazards	11 (25.0/8.5)
Biohazards	3 (6.8)
Did your safety training cover electrical safety and hazards?	
Yes	39 (88.6/30.2)
No	5 (11.4/3.9)

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